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Land Use-Water Quality Relationship

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LAND USE - WATER QUALITY RELATIONSHIP

MARCH 1976

ENVIRONMENTAL PROTECTION AGENCY
WATER PLANNING DIVISION
WASHINGTON, D.C. 20460

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Land Use-Water Quality Relationship

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Section 1

Introduction

As more attention is given to the environment and land use, quantitative descriptions of the most important relationships between pollution and land use are needed. The quantification of these relationships is necessary to support environmental quality planning and management as, for example, required by the 1972 Amendments to the Federal Water Pollution Control Act* and the 1970 Clean Air Act.** Varying degrees of comprehensive planning are suggested in these laws.***

Federal, state, regional and local environmental and land use policies, controls, and decisions have impacts on the physical environment and on local governments' economic and fiscal conditions. The impacts have been recognized in a qualitative manner, but there are few appropriate tools to quantify the impacts. If land use and emission controls are to be used effectively in implementing environmental policies it is necessary to know something about the dynamics of the local environment in which these controls are being imposed. Several interacting models† are needed which can be used at the local or regional level to facilitate understanding of these relationships. Such a set of models would permit the planner to look at the interactions between land use, socio-economic and fiscal conditions and environmental quality. The approach should consider all receiving media (air, water, land) and take into account the processes which transfer residuals from one medium to another.*

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* Public Law 92-500, October 1972.

** Public Law 91-604, December 1970.

*** The interdependency of planning processes is documented, for example, in Public Law 92-500 by Sections 201 (facilities plan), 208 (areawide plan), and 303 (basin plan).

† We use the word "models" to refer to relationships of various elements of the physical, economic, social system that are part of the land use/water quality system. We also use model more comprehensively to mean a model of the whole system. Thus we will frequently use the word model to refer to relationships among variables as well as to refer to an integrated set of relationships among variables and ultimately to describe an impact model which integrates a series of subsystem models.

This project emphasizes urban land use/environmental quality relationships. While a general framework for the analysis of these relationships has been developed, and much literature reviewed, the project has concentrated on two types of models: (1) physical impact models for assessing the environmental impact of urban stormwater runoff, and for evaluating the capacities of sewers and wastewater treatment plants; and (2) a cost distribution model for assessing the cost to be covered by different groups in response to new urban and suburban development. The schematic in Figure 1-1 outlines the context within which this project's relationships have been considered.**

In this report, Section 2 summarizes the findings of this study, Section 3 gives various recommendations as results of our findings, Section 4 provides the introduction to our analysis of land use/environmental quality relationships, and Sections 5 through 7 describe specific parts of these relationships and the formulation of the models. In Section 5 models for describing the path of waterborne residuals, from generation to assimilation in the environment, are reviewed and analyzed. There are two major paths whereby wastes from urban land uses reach receiving waters: through the discharge of sanitary sewerage, and through the washoff of dust and dirt (including nutrients) from pervious and impervious areas

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* Incineration of sludge from a wastewater treatment plant is an example of such a residual transfer.

** Note: In this scheme, landborne residuals, such as refuse, are not treated separately, but are related to either water or airborne residuals, dependent upon whether their handling affects air or water quality. Thus costs associated with handling are neglected here.

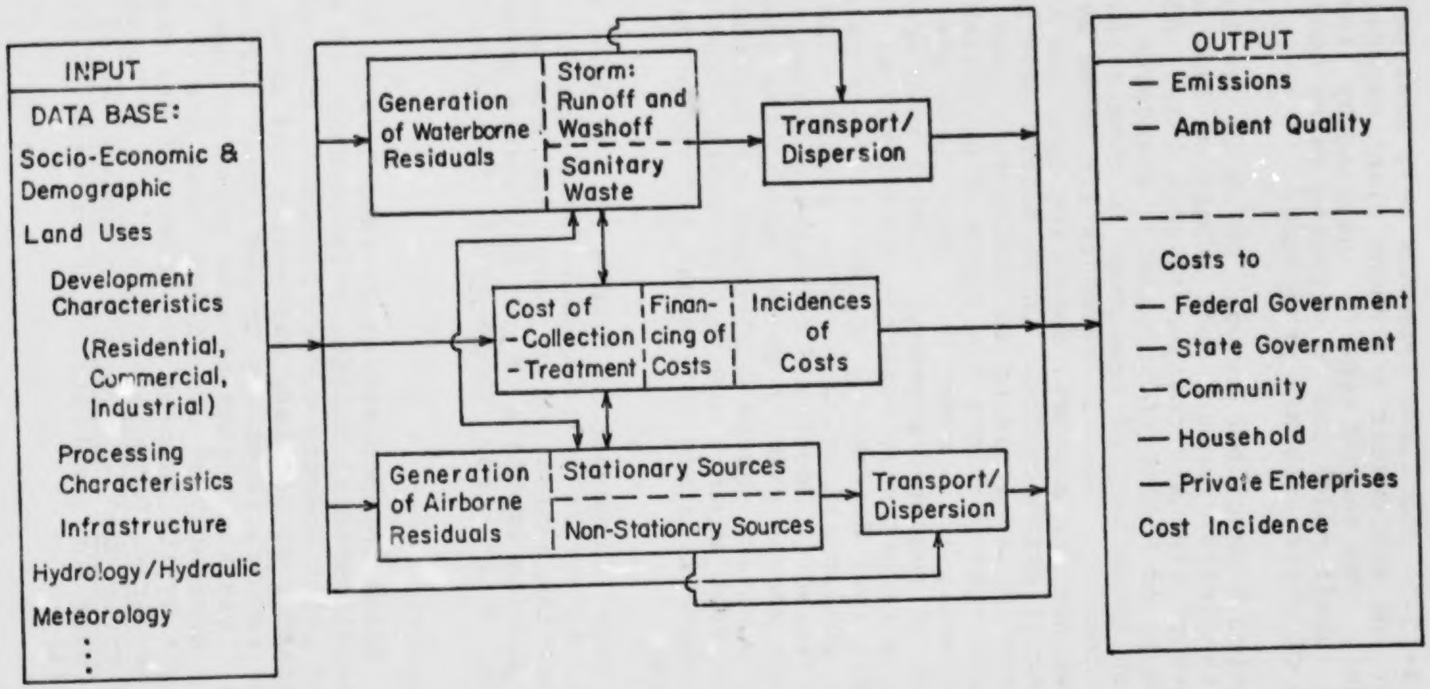
INPUT
DATA BASE:
Socio-Economic & Demographic
Land Uses
Development Characteristics
(Residential, Commercial, Industrial)
Processing Characteristics
Infrastructure
Hydrology/Hydraulic
Meteorology
⋮
Generation of Waterborne Residuals
Storm: Runoff and Washoff
Sanitary Waste
Transport/ Dispersion
Cost of
-Collection
-Treatment
Finan-cing of Costs
Incidences of Costs
Generation of Airborne Residuals
Stationary Sources
Non-Stationcry Sources
Transport/ Dispersion
OUTPUT
— Emissions
— Ambient Quality
Costs to
— Federal Government
— State Government
— Community
— Household
— Private Enterprises
Cost Incidence

Figure 1-1: Urban Land Use/Environmental Quality Relationships

(Figure 1-1).* The first type has been analyzed within the sewer and wastewater treatment plant capacity evaluation model. The second type is analyzed by linking an existing runoff model and an existing water quality model. Examples of their uses are presented.

Section 6 describes a model which is developed to predict the infrastructure cost impact of land uses or environmental standard changes (Figure 1-1). Additional development, or higher environmental standards, generally require an investment of resources to obtain the desired level of control. Such investments are borne by different sectors within the economy, depending upon institutional and financial arrangements. Three models have been developed for the analysis of infrastructure cost impacts: (1) a model that predicts the costs of providing required infrastructure; (2) a model that maps these costs into a timestream of required payments, taking into account financing arrangements, interest rates, and so forth; and (3) a model that determines the actual costs paid by different public and private sector groups. The impact model presented in Section 6 consists of these three interacting models which together accomplish these three tasks for sanitary sewage collection and treatment facilities. The cost impacts are divided among three public sectors (federal, state and local) and the private sector as a whole.

The third component of Figure 1-1, that of airborne residuals, is partially treated in this report. Section 7 discusses the generation of residuals from stationary sources, placing emphasis on air pollutants generated by residential activities. These activities generate air pollutants chiefly through the combustion of fuel for heating purposes. Thus the impacts of different heating fuel types and insulation practices are examined. No attempt has been made to deal with non-stationary sources or with the subsequent transport and dispersion of air pollutants in the environment.

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* Note: Since the project deals largely with the urban land use/environmental quality relationship, we do not talk about point sources versus non-point sources, but about discharge of sanitary wastewater and about urban stormwater runoff, referring to the latter also as aereal emissions. Discrimination between point and non-point sources is currently an unresolved issue due to the recent suit brought by the Natural Resources Defense Council (Natural Resources Defense Council, Inc. v. Russell E. Train and Environmental Protection Agency, et al., U. S. District Court for the District of Columbia, Civil Action No. 1629-73).

The linkages among the three components have not been programmed, thus the complete system conceptualized in Figure 1-1 has not been achieved during the course of this study. However, the models developed are compatible with each other. Thus they can be linked together when resources are available to develop a central control program.* In the water-related system a partial linkage between subsystems has been accomplished and has been applied to the Town of Hamden/Connecticut and the Mill River System (see Figure 1-2) within the limit of available data.

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* Environmental Protection Agency's Water Planning Division has recently funded the documentation of the models coded and developed in this project.

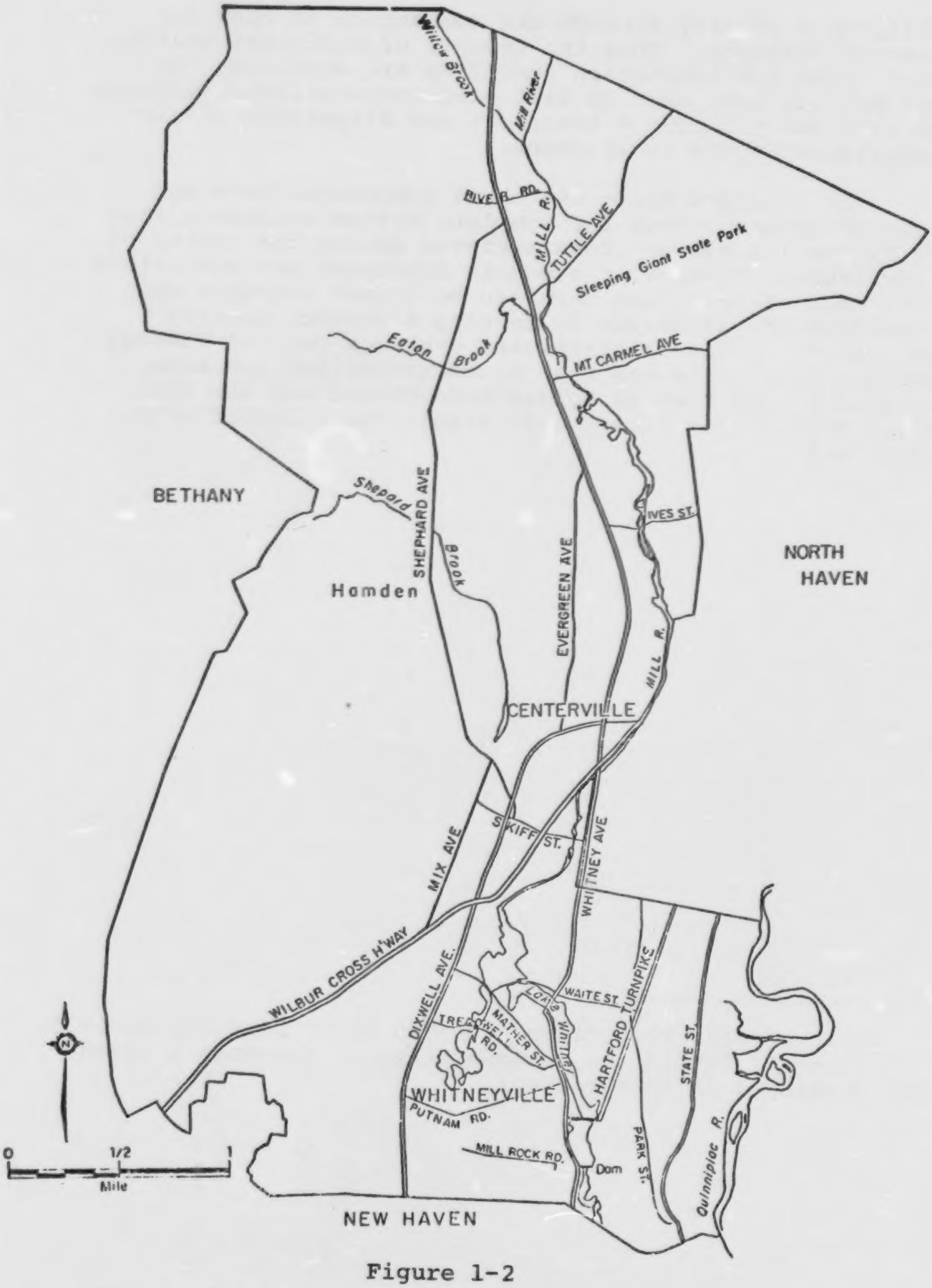
Willow Brook
Mill River
RIVER RD.
MILL R.
TUTTLE AVE
Sleeping Giant State Park
Eaton Brook
MT CARMEL AVE
BETHANY
Shepard Brook
SHEPHARD AVE
Hamden
IVES ST.
NORTH HAVEN
EVERGREEN AVE
MILL R.
CENTERVILLE
SKIFF ST.
MIX AVE
WHITNEY AVE
WILBUR CROSS H'WAY
DIXWELL AVE.
WAITE ST.
HARTFORD TURNPIKE
TREADWELL RD.
MATHER ST.
Whitney Lake
STATE ST.
WHITNEYVILLE
PUTNAM RD.
PARK ST.
Quinnipiac R.
MILL ROCK RD.
Dam
N
0
1/2
1
Mile
NEW HAVEN

Figure 1-2
Map of Hamden/Connecticut and the Mill River Basin

Section 2

Summary and Conclusions

This study on land use/environmental quality relationships has developed an approach to facilitate effective implementation of recent environmental quality legislation. This legislation requires a quantitative understanding of the relationships among various environmental and land use controls, measures of environmental quality, and regional and local fiscal and economic conditions. For example, areawide planning such as planning under Section 208 of Public Law 92-500, calls for an evaluation of environmental capacity as well as of the cost effectiveness of alternative physical and land use controls for water quality management.

In particular, the study examines the physical and fiscal aspects of land use and water quality relationships. The physical relationships were developed to describe the flow path of residuals from points of generation in various land uses to resulting instream qualities. A literature review of existing models, describing subsystems of these paths, was conducted and criteria were applied in order to select appropriate models. Models were selected for use in urban runoff and water quality evaluations. STORM, a continuous model, computes runoff, washoff and erosion, without computationally burdensome sewer routing. This model was reprogrammed and linked with the dynamic receiving water body module of EPA's SWMM. The reprogramming required considerable effort due to inadequate documentation and lack of representative examples, particularly for STORM. The combination of these two models permits evaluation of the impact of hydrographs and pollutographs (suspended solids, settleable solids, BOD_5, coliforms, nitrogen, PO_4), as they are generated hourly for each subbasin, in the water quality module; each rain event has to be considered by itself in the water quality module.

A model for evaluating sewer and wastewater treatment plant capacity was developed and coded during the study because the literature review did not reveal any model appropriate for the purposes of this analysis. The model permits assessment of existing and future sanitary flow, determination of the capacity utilization at every point in the system, and computation of points of potential overflow.

Some existing cost functions were incorporated in the cost model; others were newly developed. In particular, cost functions of sanitary laterals at the residential development level and their house connections were estimated, based on layouts of development as well as on actual sewer system design. The literature review had shown that existing functions either neglected a realistic layout or an actual engineering design. The cost model permits evaluation of costs incurred by new development or redevelopment and the distribution to different groups resulting from the cost-sharing and financing mechanisms employed by federal, state and local governments.

These models were coded and organized so that planners or other users can use them together or individually to predict the impacts of selected land development patterns and environmental control strategies.

Literature on air pollution was reviewed with the objective of developing impact models similar to those for water impacts. The review concentrated on stationary sources. Methods and estimates of emissions were compiled for residential, commercial, and industrial developments. Lack of resources precluded the development of a computerized evaluation model for emissions from stationary sources and of costs associated with their control. However, this section summarizes the state of the art on predicting air-borne emissions.

The potential of the model combination of STORM and SWMM to evaluate urban runoff has been illustrated in the case study of Hamden, Connecticut (Mill River Basin). The drawback of the area was the lack of data for detailed calibration -- a common problem for planners. Various conditions of development were selected for one of the sub-basins. Initially, STORM was used to generate emission rates, dependent upon dry antecedent and meteorological conditions. Changes of the emission rates clearly reflected different degrees of development as well as of other factors, such as different street cleaning strategies. For some of the development conditions the impacts of the resulting loads on the receiving stream were computed by SWMM. The influences of new development in only one sub-basin, as well as in all sub-basins (for example, according to the 1985 land use plan), were recognized by comparison to results for the base case, the land use configuration of 1974. The impacts were evaluated for different rain intervals over the year and for various base flow conditions in the Mill River. For these different assumptions the resulting impacts differed by orders of magnitude. While no generalizations of our results are appropriate because every river system behaves uniquely, the exercise did demonstrate the ability of the models to analyze these systems. These results have led us to conclude that a modeling package such as this could be used by various planners concerned with the impact of land use changes and/or environmental control strategies. We anticipate that these models could be useful in three situations:

1. regional planning groups formulating or modifying a regional plan, to assess environmental impacts and environmental control-related fiscal effects of alternative regional development patterns; planning agencies, such as those operating under Section 208 of Public Law 92-500, are a typical example of this category of potential users.

2. town (or local) planning groups formulating or modifying a local plan and local government policy instruments, to assess water quality impacts and environmental control-related fiscal effects of alternative local development patterns; and

3. town planners assessing the relative water quality impacts of, and the long-range water pollution control capacity investments required by a proposed development or series of developments.

We chose examples on the level of the town, but the models can be applied in the same fashion to regional analysis, such as required in 208-studies. When a town is faced with a proposed subdivision or commercial/industrial development, decisions of town authorities as to whether or not to permit the development and as to the types of fiscal and environmental requirements that should be made of the developer (such as payment of sewerage system expansion or provision of a certain minimum level of heating insulation) depend upon the types of impact information derived from this approach. At the town level, it is possible to perform the fiscal analysis without considering the finances of other communities (except when a regional authority operates wastewater treatment works). In some instances, this is also true of water quality impacts although normally a situation such as in our example, will exist: localized effects of local land use changes on the local receiving stream can be assessed, but downstream (regional) effects in the next higher order stream require understanding of changes in other upstream communities. The models could be coupled in different ways and then be used in regional planning. For most air pollution impacts, consideration of the full airshed is a necessity, with one town's air pollutant output being an input to a regional analysis. No attempt was made to devise models appropriate for these problems.

The results of this study point to a number of conclusions. First, the definition of a land use classification scheme and the creation of well-defined mechanisms for estimating generation of the residuals associated with the respective land use activities are unresolved issues. Such a scheme should, of course, facilitate the planning of pollution control, which includes controlling the mix, area/location and temporal distribution of the residual generating activities themselves. Most land use (information) schemes are not sensitive to the issues appropriate for planning environmental quality management. An appropriate classification scheme should allow for estimating residual coefficients of different degrees of refinement for a specific area. That is, it should be possible to realize a classification scheme that would allow the use of national or regional emission coefficients. Alternatively, area specific estimates of residual generation mechanisms can be performed.

Second, some tools exist which allow for quantification of some of the environmental, fiscal, and socioeconomic impacts of land use and environmental control, but there are no operational computer programs available, appropriate for the task, nor are most of the modeling formulations (presented in the literature) organized in such a way that they can be coupled into a package for interactive use by the analyst.

Third, inadequate documentation of existing, publicly available models and lack of examples representative of problems in land use/environmental quality analyses apparently tend to discourage potential users who are not well trained in modeling -- this category includes the majority of staff in public agencies who might apply these models.

Fourth, the analysis of a small sized watershed illustrated quantitatively the influence of additional development on water quality during storm events. Generally well documented qualitative knowledge that development affects water quality, was quantified within the range of accuracy required by a planning department for their impact assessments.

Section 3

Recommendations

The following recommendations point to areas where more research and better quantitative data would be useful as well as where more resources should be made available to improve the use of existing models and concepts.

1. Land use classification scheme. An appropriate set of land uses and their activities would be useful for evaluation of land use and environmental controls. This would facilitate analysis of mix, area/location and temporal distribution of residual generating activities which are used as inputs to evaluate the impact of urban pollution.

2. Dust and dirt accumulation rates and their composition. The dust and dirt accumulated on impervious areas represents the main contribution to the polluting effects of urban runoffs. No adequate data exists on the accumulation as a function of traffic, surrounding land use, air pollutant fallout, solid waste spillover, etc. Right now, planners have to rely on accumulation rates per type of land use, while rates functionally related to both individual activities and land use type are more desirable.

3. Non-urban land use. In areas of significant non-urban land use activities, these non-urban land uses should be dealt with adequately by subdividing them into an appropriate number of non-urban land uses, because each one is made up of significantly different activities and pollutant sources. Existing computer models such as STORM, should be modified to the extent that prevailing knowledge permits, to accommodate this greater degree of detail.

4. Spatial aggregation of large sub-basins. The model STORM can be used for generating urban and non-urban runoff and urban washoff from areas smaller than ten square miles, as suggested by its developers. Due to this limitation, STORM should be recoded so that multiple runs can be executed for one sub-basin without water quality routing mechanisms. This requires that the model should accept simultaneously rain hyetographs as well as time offset upstream hydrographs. The recoding would permit the application of the framework developed in this study to large regional areas without exhaustive emphasis on water quantity and quality routing in the receiving water bodies. It would also permit a stepwise aggregation from

local to regional analysis. The main basin for the local analysis would become a sub-basin of the basin of regional interest.

5. Functional relationships. New relationships have to be developed for determining temperature of runoff (mainly in the summer) as a function of antecedent conditions, and salt content of runoff as a function of salt spreading strategies of communities, salt accumulation behavior, etc.

6. Aspects of groundwater pollution. When a model becomes available which permits evaluation of pollutant behavior in groundwater, it should be added to the package. Impact of on-site sewage disposal (such as septic tanks) and of solid waste disposal sites on groundwater quality could then be included in the analysis.

7. The extension of computer packages. A number of submodules, covering aspects such as air and associated control costs, could be added to the current programs of models on the basis of existing knowledge.

8. Development of a master program. Currently the package of submodules is computationally only loosely interrelated; only STORM and SWMM are directly linked (though the linkage should be computationally improved to become more flexible). It is necessary to design a master (control) program which permits the user to operate and coordinate the models in an efficient and flexible way.

9. Cost functions, cost distribution, and equity aspects. Better cost functions have to be developed to estimate costs incurred by necessary construction of additional infrastructure. Costs of structures associated with the large number of potential stormwater management and relief strategies are a prime example. Impact of financing the infrastructure costs on various socio-economic classes and the resulting equity considerations have also not been treated adequately and need further investigation.

10. Information banking and technical assistance to environmental planning agencies. This study has suffered somewhat from the inadequate documentation of publicly available computer programs and the inadequate presentation of problems related to execution of programs under specific conditions. EPA's user assistance program (such as for SWMM) should be extended to provide agencies with advice and information on all relevant models. Only with

such assistance in addition to documentation and transfer of experience, will the available analyses and computer packages be as useful as the sponsoring agencies had originally anticipated.

11. Application. It is recommended that at least two 208 agencies with very different problems be selected as target areas to test the approach developed, to augment and refine the computer package if necessary, and to suggest additional improvements of the analyses and their performance.

Section 4

Toward the Analysis of the Land Use/Environmental Quality Relationship

A Conceptual Framework

Our approach is based on the development of classes of relationships. A list of the independent and dependent variables is presented in Table 4-1. A class of independent variables titled Ψ is suggested for the social, economic and demographic characteristics of a community or region. Such variables include population, population rate changes by cohort distribution, and property values by types of communities; each type may be further disaggregated into categories such as residential, commercial and industrial.

The second class of independent variables, Class A, refers to land use types. In this category traditional physical/geomorphological variables such as soil type, slope and cover are mixed with a set of land use variables which characterize the use to which the land is put. Examples of the latter are residential, commercial and industrial land uses.

The third class of independent variables, Class B, describes development and infrastructure characteristics. These variables indicate, for example, the extent to which a community is sewered or unsewered, the type of sewerage system, the nature of the road network and drainage systems, the type of utilities available, etc.

The dependent variables are divided into two classes. The first class, Class C, includes measures of the costs of land use development and the distribution of the costs among communities and socio-economic groups (which we refer to as the cost incidence). Some of the cost measures suggested are capital and operation and maintenance (O&M) costs expressed on a per capita and per acre basis. There is the further potential breakdown by income and measures of tax rate changes.

The second class of dependent variables, Class D, consists of variables which represent environmental quality indicators. These variables are divided into two subclasses, emission factors (D_1) and quality indicators (D_2). Table 4-1 indicates a list of potential emission factors measured by media on a per acre basis and a series of indicators characterizing the environmental quality in time and space.

Table 4-1

Summary of Possible Independent and Dependent Variables

Independent Variables			Dependent Variables	
Socio-economic and Demographic ψ	Land Use Type A	Development Characteristics and Infrastructure B	Cost and Incidence* C	Emission Factors D_1 Quality Indicators D_2 D
Cohort distribution	Single family - 1-3 lot sizes - 3 soil types - 2 depths of bedrock - 2 groundwater conditions - slope	Unsewered Separated sewers Combined sewers Storage - on line - off line	K**/capita public federal state local K/capita private	Emission by Media (pollutant/space unit/time unit) BOD SS N P coliform SO_2 NO_x particulates etc.
Community profile - residential - commercial - industrial	Multi-family - 4 densities - soil type - groundwater - slope	Utilities - heating systems · oil · gas · electric	K/acre O&M*** (See K) Implicit tax rate	Ambient Indicators by Media (pollutant-unit or concentration/time-unit color turbidity coliforms

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* Distribution of costs among communities and socio-economic classes.

** K is capital costs.

*** O&M is operation and maintenance costs.

Table 4-1 (continued)

Socio-economic and Demographic ψ	Land Use Type A	Development Characteristics and Infrastructure B	Cost and Incidence* C	Emissions factors D_1 Quality Indicators D_2 D
	Commercial - strip 2 densities - shopping center 2 scales - soil - groundwater - slope	Water - wells - public · surface · groundwater	Time streams	Ambient Indicators by Media (Continued) ± algae DO, BOD SO_2 particulates CO NO_x etc.
		Road		
		Percent impervious cover		
	Industrial	Water using appliances		Open Space - type - quality - amount
	Agriculture	- irrigation of lawn		
	Woodland	- kitchen		
	Meadow	Solid waste collection		

Relationships among the classes of variables can be characterized by three categories. The first expresses the cost and incidence variables (Class C) as a function of the variable classes Ψ, A and B: $[C=f(\Psi, A, B)]$. Thus we are suggesting that cost, fiscal impact and incidence variables are a function of all three classes of independent variables. The second category of relationships links emission factors and independent variable Classes A, Ψ, and B; that is, emission factors can be expressed as a function of land use type variables, socio-economic variables and variables describing the development and its infrastructure characteristic: $[D_1=f(A, B, \Psi)]$. The third class of relationships relates quality indicators to the independent variables: $[D_2=g(A, B, \Psi)]$. A subset of these relationships relates ambient quality indicators explicitly to emission factors (and hence implicitly to variables of Class A, B, and Ψ) using an additional class of functional relationships T, which we shall call transfer functions. The transfer function describes the transport, dispersion and assimilation of the emissions. Thus we can calculate ambient quality in time and space $[D_2=f(D_1, T)]$.*

In order to analyze residuals and economic impacts in the overall system characterized by the relationships postulated among the variable classes, the physical and economic subsystems have to be identified which when linked together contain the above relationships. Relevant subsystems were investigated on both the water and air side; but the water side was emphasized in the review and analysis of models.

Criteria for Evaluation of Models of Subsystems

A large number of models describing various aspects of the land use/environmental quality relationship can be found in the literature. There exists** for various subsystems a number of summaries that cover much of the material on the subject written in the last decade. The complexity of the models, the necessary data requirements and the resources needed to solve the models vary widely. Our literature review is aimed toward determining what earlier efforts would be useful in synthesizing a chain of models which adequately describes the land use/environmental quality relationship. We have thus evaluated each model in terms of its potential within a nested model.*

---

* In the cases where a specific land use, such as wetlands, explicitly affects the transport dispersion and assimilation, then the function becomes $[D_2=f(D_1, A, T)]$.

** For example, on the water side see E. A. McBean and D. P. Loucks, "Planning and Analysis of Metropolitan Water Resources System," Technical Report No. 84, Cornell University Water Resources and Marine Sciences Center, Ithaca, New York, June 1974.

We have established a number of criteria for model evaluation; a thorough evaluation should:

- provide sufficient justification for the use of a particular model (i.e., quantitative reflection of the mechanism under investigation) within the spatial and temporal context of the study;**
- consider the details of input/output and of internal relationships of each model within the total framework;
- ensure the homology of the directly connected models, i.e., the output of a model must be structurally equivalent to the inputs of the models with which it integrates;
- estimate the sensitivity of the total framework to a particular model; a high sensitivity would require

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* We speak of nested models when a set of models is nested in such a fashion that outputs of one model are inputs of other models (see Meta Systems Inc, "Systems Analysis in Water Resource Planning," prepared for National Water Commission, July, 1971; published by Water Information Center, Inc., Port Washington, N.Y., 1975).

** Generally many assumptions and simplifications are made which frequently prohibit judging a model adequate a priori for other purposes than the one which caused its development. It is worth noting the argument presented by various operations research investigators (e.g., Hillier and Lieberman, 1967) that the appropriate criterion for judging validity of a model is whether within the scope of the problem the model predicts the relative effects of alternative courses of action with sufficient accuracy to permit adequate analysis of that action and decision on it; see Hillier F. and G. Lieberman, Introduction to Operations Research, Holden Day, Inc., San Francisco, 1967.

a model which is well detailed and reliable, but would also imply that if such a refined model were not available the connected models at the next levels might be less rigorous;

- consider the temporal and spatial resolution of the model in the context of the temporal and spatial framework of the total analysis;
- determine the availability of data to calibrate and, if possible, to verify the model; a complicated model can be used to its full potential only when an adequate data base is secured. Otherwise a less complicated model with lesser data requirements might produce superior results. It is possible to fit every model to a limited data base; but the quality of the model's performance decreases with the number of parameters which must be set arbitarily;
- estimate the computational resources needed to apply the model, in the light of its proposed results and of its position in the macromodel;
- evaluate if the type of model -- both the approach and its generated output (in time and space) -- is useful for the planning methodology. It is often desirable to use a model which has already been prepared to reduce the costs of coding; but such a model might be irrelevant to a planner or to a designer or both.

We have tried to apply these criteria carefully in the review of the literature pertinent to the modeling of the land use/environmental quality interrelations and in our effort toward the synthesis of a land use/environmental quality macromodel. In the following sections of the report the particular relationship being focused upon is defined, a review of pertinent analytical factors and existing models or modeling approaches is made, and then features to handle the relationship are synthesized.

Section 5

Land Use/Water Quality: Physical Impact

Subsystems of the Urban Land Use/Water Quality Relationship by Definition

In order to develop a chain of mathematical models reflecting our framework and in order to review pertinent literature, a scheme was devised to display the connections between types of land use and water quality via relevant activities and events (Figure 5-1). Specific land use types (commercial, industrial, and residential) imply aspects of the classes of independent variables, ψ, A, and B (see Table 4-1): density of residences, population, and commercial and industrial activity centers; cohort distribution of residences, type of activities; percent open space; and percent imperviousness and infrastructures such as roads, utilities, etc. Functions inherent in land use types (such as living, manufacturing, marketing, expanding, etc.) imply use of resources and their subsequent transfer into a different state. These functions are reflected in water consumption, in generation of residuals (SS, BOD, P, N, etc.) in traffic, in activities (such as loading of trucks, repairs, recreation, etc.) on impervious and pervious areas, and in construction of activity centers. The next level of the chart is comprised of the emission of wastewater and of solid wastes as well as the accumulation of pollutants on impervious and pervious areas and the erosion potential. The emissions are strongly related to the land use types (see above). Accumulation of dust and dirt (being composed of pollutants such as dissolved, suspended, and settleable solids, BOD, N, PO_4, coliform, etc.) is caused by traffic, air pollution fallout, and other incidents as well as by construction activities. The erosion potential is dependent not only on temporary construction events but also on the physiography and topography of an area. The next level in the chart refers to collection and transport systems from the point of generation (or point of contact in the case of rainfall) to the point of discharge into the aquatic environment, or littoral environment in cases of where wetlands are the receiving body. Wastewater can be removed from the point of generation by public collection systems (separate or combined sewers) or by private on-site disposal systems if sewers are not available (see also infrastructure variable Class B, Table 4-1). Solid wastes will be either collected by collection vehicles (private contractor, publicly contracted collector, or public collection) or will be taken to the handling facilities by each individual

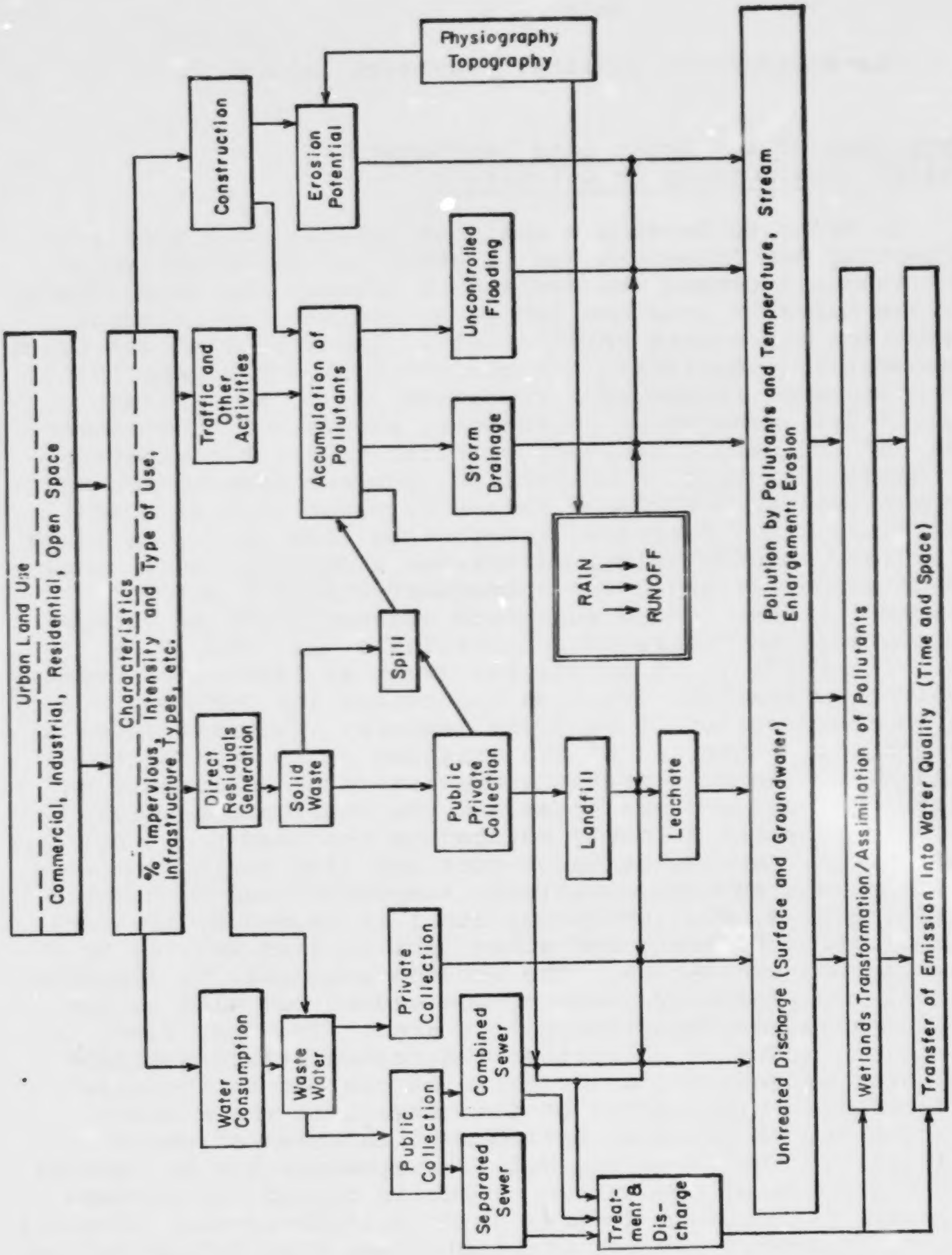
Urban Land Use
Commercial, Industrial, Residential, Open Space
Characteristics
% Impervious, Intensity and Type of Use, Infrastructure Types, etc.
Water Consumption
Waste Water
Direct Residuals Generation
Solid Waste
Traffic and Other Activities
Construction
Physiography Topography
Erosion Potential
Accumulation of Pollutants
Uncontrolled Flooding
Storm Drainage
Spill
Public Private Collection
Private Collection
Public Collection
Combined Sewer
Separated Sewer
Landfill
Leachate
RAIN
RUNOFF
Treat-ment & Dis-charge
Untreated Discharge (Surface and Groundwater)
Pollution by Pollutants and Temperature, Stream Enlargement: Erosion
Wetlands Transformation/Assimilation of Pollutants
Transfer of Emission Into Water Quality (Time and Space)

Figure 5-1: Flow Chart of Connections Between Urban Land Use Types and Water Quality

household.* It should be noted that spills also contribute to the accumulation of pollutants. Stormwater and the pollutants which it carries will be removed through drainage facilities (combined sewers or stormwater conduits, including detention facilities) or will run off directly to a receiving water body.

The next level is concerned with treatment and then discharges of the residuals of all activities into the aquatic and/or littoral environment. It should be noted that all discharges are divided into "treatment and discharge" and "untreated discharge" such that the category "treatment and discharge" covers all those discharges which are currently subjected to permit application under the National Pollution Discharge Elimination System (NPDES).

We are concerned with the quantity as well as the quality of each discharge. Quality can be controlled by treatment plants and other means, such as street cleaning or sewer flushing. The amount of pollution entering the receiving water body depends on the portion of untreated to treated discharges. All discharges from the sanitary sewers of a separate sewer system are categorized as treated discharges. The quality of the latter depends on the degree of treatment in the treatment plant. If the combined sewer system works properly during dry weather flow, the sanitary flow in combined sewer systems also falls into this category. If the overflow devices work improperly, the malfunctioning has to be recognized and recorded in order to calculate the sanitary flow which is discharged without treatment. The stormwater flow in combined systems will be discharged largely untreated. The quality of overflowing and bypassing waters of the combined flows has to be adequately adjusted due to mixing with sanitary flows. Discharges from storm drainages in a separate sewer system are largely untreated.* The quality of these discharges depends mainly on the washoff rate of accumulated dust and dirt from urban areas and on the deposits in the system. Generally all unknown, unmeasured, or uncontrolled flows from combined or separate storm drainages as well as other systems will be dealt with as untreated discharges to surface and groundwater. This includes stormwater which may enter the receiving water body by seepage from conduit system, overland flow, gullies, and minor tributaries.

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* Note that some treatment facilities for stormwater have been built in the last decades (see, for example) Lager, J. A., Stormwater Treatment: Four Case Histories, Civil Engineering-ASCE, December 1974).

The impact of private wastewater collection systems is of interest only in terms of quality. Infiltration from poorly operating on-site wastewater disposal systems affects the groundwater quality; runoff from inadequately operated leaching fields might affect the quality of surface and groundwater (which in turn might further influence surface water quality). The effects of solid waste disposal areas are also limited to quality aspects. There exists evidence that infiltration of rain water into solid waste landfills (or any other land disposal area) produces leachate, which in the case of inadequate subsoil greatly affects the groundwater quality.

The total quantity as well as the peak discharge of urban stormwater runoff can have significant effects. The fast runoffs from urban areas have a high potential to cause flooding in urban conduits as well as in receiving streams. This can lead to stream enlargement by erosion of the banks and to other channel effects. Depending on the physiographic and topographic characteristics as well as on man's land usages and construction activities, rainfall and subsequent runoff might cause heavy erosion, which, in turn, could lead to sedimentation in artificial and natural conduits. A high degree of imperviousness over large areas contributes to the reduction of the base flow in streams, mainly in dry seasons. Thus heavy runoff during these seasons might influence the temperature in the stream.

In this framework all discharges will be ultimately transferred into temporally and spatially distributed determinants of water quality of ground and surfacewater. The transfer depends on the characteristic of the receiving water body and the emission components.

A Brief Review of Existing Models

The network of the land use/water quality relationship typified in Figure 5-1 will be used as a basis for discussing mathematical models found relevant along the lines of the established criteria. Estimates of, and approaches to estimating emissions are considered first for discharges consisting primarily of sanitary wastes generated at a point of activity (point-generation), then for discharges largely caused by precipitation on urban areas (areal generation). The latter includes both surface accumulations of pollutants and their washoff. Next, some existing approaches to modeling urban runoff are reviewed. Models for other emissions which interface with water quality including solid waste and on-site wastewater disposal follow, and finally, models for transport/dispersion and assimilation are examined.

Estimating Point-Generation Emissions of Liquid Wastes

Unfortunately most of the emission data collected on water use and wastewater characteristics are highly aggregated. With water use, for example, data are generally available on total community usage, while for wastewater, most flow and quality characteristics are measured at the "end of the pipe" and therefore represent the effects of a combination of land uses. As a result, engineers who develop design factors to apply to specific land use types, whether for a particular project or for general reference, have to rely to a considerable degree on their judgment and experience in disaggregating the available information. Over the years this process has evolved a set of more or less generally accepted "rules of thumb" for use in wastewater management planning. The quantities 0.17 lb. BOD_5/capita/day, 0.20 lb. SS/capita/day, and 100 gpcd appear extensively in the wastewater engineering literature.*

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* Investigators increasingly are turning to different methodologies in attempting to develop reasonably accurate emissions factors. Recently Meta Systems Inc has formulated a framework for the evaluation of generation factors and has shown how recent studies fit within that framework. Mechanistic and econometric approaches, individually or combined, were suggested for determining the residuals. The econometric approach seeks to avoid the detailed mapping of consumer selections into residuals by neglecting the choice of technology and its factor inputs. It assumes a fixed technology and attempts to map directly from certain key factors in the consumer's decision, particularly income, to residuals. Thus the approach follows in the spirit of much of the traditional econometric literature on consumer demands. The mechanistic approach, on the other hand, ignores the consumer's behavior and socio-economic basis and concentrates on obtaining the appropriate technology coefficients. This approach, for instance, should allow the planner to estimate the desired residual coefficients from a detailed analysis of the appliances and their uses in each water-consuming and waterborne generating part of the household and the subsequent summation of all usages.

In both the econometric and mechanistic approaches

Residential wastewater generation is correlated to water use, so that water use estimates can be applied for estimating wastewater quantities. The average per capita water use in the U.S. was estimated to be 147 gallons per capita per day (gpcd) in 1954.** With the assumption that 40 percent of this represented domestic usage, it was concluded that the average residential use was about 60 gpcd. Assuming that 60 to 80 percent of this use is non-consumptive,*** we arrive at an estimated range of 36 to 48 gpcd for wastewater generation. This is considerably less than the 100 gpcd figure commonly cited but is in general agreement with values cited, for example, by Ligman _et al._†

There exist a number of models, aimed at predicting residential water consumption. Linaweaver,†† for instance, used an econometric approach for his analysis. He found that the principal factor influencing total annual water use is the total number of homes. Three additional factors of significance are the economic level of the consumer, climate, and charge mechanism. Linaweaver tested his hypothesis regarding the influence of the "economic level of the consumer" on water usage by analyzing water use data from 29 areas and by fitting a regression equation which contains average domestic use per dwelling unit (gpd) as the dependent and average assessed valuation of property (thousands of dollars) as the independent variable. Additional analysis of residential water demand by Howe and Linaweaver* resulted in an equation containing age of dwelling unit, number of persons per dwelling unit, and average water pressure in addition to the initial independent variables. Based on extensive analysis of water use data from 21 eastern and western drainage basins, this study indicated that only the market value of the dwelling unit and the charge mechanism (metered versus flat rate) were statistically significant in formulating regressions with average daily water use as the dependent variable.

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* (footnote continued from previous page)

different levels of aggregation may be employed, depending upon the purpose of the analysis, the data, and time available for the study. See for details R.J. deLucia, J. Kühner, and M. Shapiro, "Models for Land Use/Water Quality: Some Observations on What Exists and What is Needed," presented at the 47th National ORSA/TIMS Meeting, Chicago, April 30, 1975.

** Select Committee on National Water Resources, U.S. Senate, Water Resources Activities in the United States, Government Printing Office, Washington, D.C., 1960.

*** Metcalf and Eddy, Inc., _Wastewater Engineering_, New York, McGraw-Hill, 1972.

† K. Ligman, N. Hutzler, and W.C. Boyle, "Household Wastewater Characterization," _J. Environmental Engineering Div._, ASCE, vol. 100, EE1, February, 1974, pp. 201-215; Ligman, _et al._, tried to develop household quantity and quality emission data by combining an empirical study of the biochemical composition and usage patterns of common household appliances with additional flow and composition data available in the literature.

†† F. Linaweaver, "A Study of Residential Water Use," report prepared for F14A, Department of Housing and Urban Development, Washington, D.C., 1967.

Determining wastewater generation from particular industrial or commercial developments is more difficult than from residential areas because types of non-residential activities influence significantly the amount of wastewater and emissions. However, land use and sewer planners who must base their planning on projections 20 years or more into the future are seldom in a position to predict the types of activities which will locate in a particular industrial or commercial zone, even less so the intensity of the ultimate use. At this level planners are forced to work with emission factors on a per acre basis. Not surprisingly, the result is that projections vary widely across the country, as indicated in Table 5-1.

It seems probable that commercial development will continue to be of either the strip commercial or shopping center variety for most suburbanizing areas, and industry will continue to select land-intensive production combinations. Based upon design values employed in areas where these types of activities are prevalent, we have found that commercial and light industrial wastewater flows can be expected to range from 2,000 to 10,000 gal/acre/day.

Estimates of per capita pollutant generation have been developed mainly from combining estimated flow rates with

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* C.W. Howe and F.P. Linaweaver, "The Impact of Price on Residential Water Demand and Its Relation to System Design and Price Structure," Water Resources Research, vol. 3, no. 1, 1967.

Table 5-1

Wastewater Generation of Non-Residential Land Uses

Location	Commercial (gpd/acre)	Industrial (gpd/acre)
(unreported)*	15-60,000	14,000
Cincinnati, Ohio**	40,000	-
Los Angeles, California**	11,700	15,500
Kansas City, Missouri**	5,000	10,000
Memphis, Tennessee**	2,000	2,000
Buffalo, New York**	50,000	-
Santa Monica, California**	9,700	13,600

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* Source: Sigurd Grava, Urban Planning Aspects of Water Pollution Control, New York, Columbia University Press, 1969.

** Source: Design and Construction of Sanitary and Storm Sewers, American Society of Civil Engineers and the Water Pollution Control Federation, 1969.

available data on wastewater composition. Using this approach, we have obtained the table of emission factors (Table 5-2), which is calculated by multiplying the concentration for a medium-strength sewage (Metcalf and Eddy*) by estimates of 50, 100, and 150 gpcd to obtain a reasonable range of emission rates.

For comparison, the results of Ligman et al.,** are presented alongside the computed values. It can be seen that the Ligman study, which estimates loadings from individual water uses within the house, agrees well with the medium estimated value.

Emission factors for residential wastewater generation have been reported not only on a per capita, but also on a per acre*** and per bedroom† basis. From the standpoint of land use planning applications, one of the latter types of coefficients, particularly the per acre basis, might seem more attractive. However, such figures have assumed certain values for number of persons per dwelling unit and dwelling units per acre and these assumptions often are not stated explicitly. As a result, use of these coefficients can lead to significant inaccuracies. It is more appropriate to start with a per capita flow and then build up acreage values based on explicit assumptions as to dwelling unit composition and density. For example, Grava†† lists 8,000 gal/acre/day as a figure for medium-cost residential housing. At 100 gpcd and 3.5 persons/dwelling unit, this implies a density of 23 units/acre, over five times the figure for typical medium-cost single-family homes in suburban settings.

For most light industrial and commercial land uses, pollutants are derived primarily from the sanitary wastes of employees and shoppers. As a result, assumptions regarding residential waste strengths can be applied to those wastes as well. For certain commercial establishments such

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* Metcalf and Eddy, Inc., op. cit.

** Ligman, et al., op. cit.

*** Grava, Sigurd, Urban Planning Aspects of Water Pollution Control, New York, Columbia University Press, 1969.

† Salvato, Joseph A., Jr., Environmental Engineering and Sanitation, New York, John Wiley & Sons, Inc., 1972.

†† Grava, S., op. cit.

Table 5-2

Residential Emission Factors for Pollutants

Pollutant	emission (lb/capita/day) low	medium	high	Ligman (et al.)*
Total Solids	.292	.584	.876	.505
Suspended Solids	.083	.167	.25	.198
BOD_5	.083	.167	.25	.174
Chemical Oxygen Demand	.209	.417	.625	-
Total Nitrogen	.017	.033	.050	-
Total Phosphorous	.004	.008	.013	.009

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* Ligman, *et al.*, *op. cit*.

as restaurants and laundries and for most heavy industries, this generalization is not valid. In the case of commercial land uses, the effect of a few individual establishments is likely to be averaged -- which means lost in the large number of economical uses associated with any reasonably sized planning area. For heavy industries virtually no useful generalizations can be made. Salvato* presents an extensive table of BOD and SS loadings per unit of product for major polluting industries. Again, however, unless the planner has some reasons to believe that a particular industry will be likely to locate in a specific area, these tables are of little use.

Assuming continuation of the present pattern of suburban commercial and light industrial development, emission ranges for these land uses can be estimated from the flow range cited previously and the medium-strength sewage concentrations employed for residential emissions (Table 5-3).

Estimating Areal Generation and Emissions of Liquid Wastes

Quantitative knowledge about areal pollution is still at a very crude stage. Available data are of a very aggregated nature and at best can give order-of-magnitude estimates of potential loadings from different land uses. In general, these sources can be divided into two categories -- those associated with stable land uses and those associated with transient activities. Included in the former category is runoff from the continuous use of land for some particular urban or non-urban activity, such as forestry, pasture, farming, and residential dwellings after landscaping is completed and new drainage patterns established.** The range of constituents emitted from these sources, particularly urban land and active agricultural land, covers virtually the entire range of identified pollutants, from oxygen demanding organics to heavy metals and complex organic chemicals.

From a long-range standpoint pollution from stable land uses are of most concern to planners. In the short term however, transient construction or silviculture activities may play a much larger role in determining water quality.

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* Salvato, op. cit.

** Note, areal sources based on non-urban activities are called "Non-Point Sources".

Table 5-3

Emission Factors: Commercial and Light Industry

	lb/acre/day
Total Solids	11.7 - 58.4
SS	3.3 - 16.7
BOD	3.3 - 16.7
COD	8.3 - 41.7
N	0.67 - 3.3
P	0.17 - 0.83

The problem of erosion and sedimentation due to construction activities is well known. However, a variety of other pollutants are also generated, including fertilizers, synthetic organics, metals and a variety of inorganic salts used for soil stabilization. Many of these are transported by sediment movement after adsorption onto the fine soil particles. Measures to control erosion such as early planting of grass at construction sites can lead to other types of pollution, notably runoff of fertilizers employed to speed growth.

In recent years attempts have been made to improve the quantitative knowledge about the magnitude of areal source pollution by investigating the activities of land use types in detail. This has been attempted with stable urban land use types by concentrating on deriving accumulation rates of dust and dirt on surface areas (mainly impervious areas) and then by computing washoff load and quality of runoff based on these rates and the magnitude of precipitation. These attempts are described before some of the aggregated emission data are presented and discussed.

1. Surface Accumulation of Pollutants. Data show that contaminants from impervious surfaces are by far the predominant pollutants of urban stormwater runoff. Therefore, it is desirable to understand the pollutant accumulation process in order to predict the rates of solid accumulation and the composition of their pollutants dependent upon land use activities (traffic, construction, littering, etc.). A few published data on this subject exist;* however, use of these data for general application is questionable. The data are not disaggregated into accumulation rates per activity and activities per land use type but are aggregated merely on the basis of land use types. Each land use type exhibits a different rate of dust and dirt accumulation per dry day per 100 feet-curb (Table 5-4). There are also differences among land uses in the pollutant composition per gram of accumulated dust and dirt.** The latter is obvious because land use types differ in their prevailing activities, which in turn cause different pollutant generation patterns (see Table 5-5). The number of dry days prior to the storm event is important in terms of total mass built

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* For example, American Public Works Association (APWA), "Water Pollution Aspects of Urban Runoff," Federal Water Pollution Control Administration, Contract WP-20-15, 1969.

** APWA, *op. cit.*

Table 5-4

Dust and Dirt Accumulation*

Land Use	Pounds DD**/dry day/100 ft-curb
1. Single family residential	0.7
2. Multi-family residential	2.3
3. Commercial	3.3
4. Industrial	4.6
5. Undeveloped or park	1.5

* Based on 1969 APWA report for Chicago, op. cit., p. 56.

** DD = dust and dirt.

Table 5-5

MG Pollutant Per Gram of Dust and Dirt[a] for Each Land Use Type

Parameter	Land Use Type[†]				
	1	2	3	4	5[b]
SS	1000.0	1000.0	1000.0	1000.0	1000.0
BOD	5.0	3.6	7.7	3.0	5.0
COD	40.0	40.0	39.0	40.0	20.0
Coliforms[c]	1.3×10^6	2.7×10^6	1.7×10^6	1.0×10^6	0.0
Settleable Solids	100.0	100.0	100.0	100.0	100.0
N	0.48	0.61	0.41	0.43	0.05
PO_4	0.05	0.05	0.07	0.03	0.01
Grease[d]	1.00	1.00	1.00	1.00	1.00

[a] Most values are based on 1969 APWA report, op. cit.

[b] Values for undeveloped and park lands are assumed (coliform estimation unreasonable).

[c] Units for coliforms are MPN/gram.

[d] All values are assumed.

[†] Land use types 1 to 5 are defined in preceeding Table 5-4.

Source: SWMM Interim Revised User's Manual, Office of Research and Development, EPA, August 1974, (Draft).

up for the potential washoff load. The frequency of street cleaning also plays a role. If a cleaning takes place before the next rain, the potential washoff load is reduced in relation to the cleaning equipment's efficiency. If the interval between storms is long and the cleaning frequency is low, significant loadings of suspended and settleable solids and of organic demands (BOD, COD) are imposed on the system at the beginning of the storm. The pollutant accumulation rates of APWA's Chicago Study* are the basic data used in most of today's modeling efforts.

APWA's study supplied many new data and compiled and analyzed others, but a number of presentations are misleadingly definitive in appearance. For example, in that study, Table 4 (page 30)** contains estimates of monthly street litter components from a 10-acre residential area in Chicago (tons/month). The data are presented not only by month but also by component. The only component that varies by month, however, is "vegetation." The important component "dust and dirt" accumulated identically in spite of the fact that several plausible hypotheses could be suggested that would anticipate seasonal changes due to hydrology and climate as well as to man's activities. It should also be pointed out that in the Chicago data approximately 49 percent of the "dirt and dust" fraction was insoluble--essentially all of it is potentially suspended solids.*** Table 5-6 strongly suggests that the Cincinnati overflow data† used in the APWA study do not resemble the (total) "dirt and dust" fraction from Chicago. Clearly these are different materials. On the other hand, a U.R.S. Research, Inc.,†† study examined the average composition of dirt and dust from ten cities. With some variation the total dust and dirt was similar to that of Chicago (after all Chicago data contributed to the average). Table 5-7, however, shows that when corrected for particle size, the dirt and dust

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* APWA, op. cit.

** APWA, op. cit.

*** T. Flaherty, Process Research, Inc., personal communication, 1975.

† S. R. Weibel et al., "Urban Land Runoff as a Factor in Stream Pollution," J. WPCF 37, July, 1964.

†† J. N. Sartor, and G. R. Boyd, "Water Pollution Aspects of Street Surface Contaminants," U.R.S. Research Company, San Mateo, California, for U.S. E.P.A., E.P.A.-R2-72-081, November, 1972.

Table 5-6

Comparison of Cincinnati Overflow Rate and Chicago's Dust and Dirt Data

	Cincinnati Storm Runoff	Chicago Dirt and Dust
BOD_5	4.5-12%	0.36-0.77%
COD	33-58%	3.9 -4.0%
VSS	20-30%	0.38%
PO_4	0.25-0.48%	0.005-0.007%
Total-N	0.9 -1.6%	0.51 -0.061%

Table 5-7

U.R.S. Data Corrected for Particle Size Less Than 43μ

	URS Research, Inc. Dirt and Dust < 43μ
BOD_5	5.8%
COD	33.0%
VSS	31.0%
PO_4	0.88%
Total-N	0.77%

component less than 43μ was reasonably similar to the Cincinnati runoff. This explanation is intuitively attractive because the finer materials are normally more susceptible to being washed off.

The difficulties involved in improving the data base for modeling the quality of runoff are underlined by the fact that very few additional data have been published. Table 5-8 summarizes some of these data.*

A simple model has been formulated for the accumulation process by taking into account for each land use type total curb length, dry days, street cleaning, and the correspond-ing dust and dirt accumulation rate.** The mass of dust and dirt is then separated into various pollutants by using empirical fractions dependent on the land use (see above). Regression equations have been published recently which calculate accumulation for each land use as function of traffic volume, pavement conditions, and time since rainfall or sweeping.*** Verification of the results has not been reported.

2. Areal Emissions. Some of the information available in the literature on urban areal and non-point source emission rates for BOD, CO, NO_3-N, Total N, Total P, and sediment has been summarized and is presented in Table 5-9. The first seven columns represent emissions from stable land uses. The tenth column is for construction activity; for comparative purposes the emissions from untreated and treated residential wastes at 3 dwelling units/acre are listed in columns 8 and 9. An average of 3.5 persons per dwelling unit is assumed for the latter estimates. Table 5-9 is

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* The derivation of these rates is described in "Progress Toward Synthesis and Integration of Land Use and Environ-mental Quality," Working Paper no. 4, prepared for E.P.A. by Meta Systems Inc, Contract no. 68-01-2622, June, 1975.

** "Stormwater Management Model, vol. 1, Final Report," 11024 DOC 07/71, Metcalf and Eddy, Inc., University of Florida, Gainesville, and Water Resources Engineers, Inc., Report for E.P.A, July, 1971.

*** R. Sutherland and R. McCuen, "A Mathematical Model for Estimating Pollution Loadings in Runoff from Urban Streets," Preprint from Proceedings of the International Conference on Mathematical Models of Environmental Problems, Southhampton (U.K.), September, 1975.

Table 5-8

Comparison of Accumulation Rates (lb/dry day/10,000 ft) in Literature[1]

	SUS					SET					BOD_5					N					PO_4				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3*	4	5	1	2	3**	4	5
Single	7.0	15.54	6.63			,7	1.55	.66			.35	2.8	1.88			.034	.28	.13			.0035	.028	.17		
Multi	18.4	36.8		49.5		1.84	3.68		4.95		.83	6.62		3.78	4.2	.328	1.104		.8		.0115	.092		.4	
Commercial	56	112.2	90.6	15.02		5.61	11.2	9.06	1.5		2.54	20.33	2.89	18.74	1.2	.135	1.06	.22	.14		.0231	.198	.23	.12	
Industrial	31		335.2 106.1	117.66		3.22		33.5 10.6	11.77		1.38		3.32 2.69	24.04	8.0	.198		.246 .175	1.4		.0138		.54 .2	1.2	
OS	14	102.12				1.65	10.21				.75	18.4		8.15		.072	1.84				.0075	.184			

[1] Literature values had to be converted to this format of accumulation rates by making various assumptions.

1: American Public Works Association (APWA), "Water Pollution Aspects of Urban Runoff," Federal Water Pollution Control Administration, Contract WP-20-15 (1969).

2: Roesner, et al., "A Model for Evaluating Runoff-Quality in Metropolitan Master Planning," ASCE Urban Water Resources Research Program, Technical Memorandum No. 23, April 1974, p. 62.

3: "Storm Water Pollution from Urban Land Activity," AVCO, Economic Systems Corporation, "Water Pollution Control Research Series, Federal Water Quality Administration," Report No. 11034, FKL 07/70 (1970).

4: Sartor, J. D., and G. B. Boyd, "Water Pollution Aspects of Street Surface Contaminants," URS Research Company, San Mateo, California, for U.S. Environmental Protection Agency, EPA-R2-72-081, November 1972 (Table 45, p. 144).

5: Graham, Ph. H., L. S. Costello, and H. Mallon, "Estimation of Imperviousness and Specific Curb Length for Forecasting Stormwater Quality and Quantity," J. Water Pollution Control Federation, Vol. 46, No. 4, April 1974.

* Organic Kjeldahl Nitrogen.

** Soluble Orthophosphates.

Table 5-9

Non-Point Source and Urban Stormwater Emission Rates (lb/acre/yr)

				Irrigation in Western U.S.				3 Du/Acre Sewage		
	Forest	Range	Active Cropland	Surface Drainage	Sub-surface Drainage	Cropland Tile Drainage	Urban	Treated*	Untreated	Construction
COD (lb/A/Yr)	-	-	-	-	-	-	196-276	240.	1598.1	-
BOD (lb/A/Yr)	-	-	-	-	-	-	27-45	95.9	639.3	-
NO_3-N (lb/A/Yr)	.62-7.8	.62	-	-	74.	-	-	63.4	0.0	-
Total N (lb/A/Yr)	2.7-11.6	-	.09-11.6	2.7-24	37.4-166	.27-11.6	6.2-8	63.4	127.8	-
Total P (lb/A/Yr)	.027-.27	.07	.05-2.6	.89-3.92	2.7-8.9	.009-.26	.98-5.0	12.8	31.9	-
Sediment (lb/A/Yr)	~ 75	~750	~ 15,000	-	-	-	~ 16,000	31.9	213.1	3,000 - 375,000

Source: Loehr, Raymond C., "Characteristics and Comparative Magnitude of Non Point Sources," JWPCF, 46(8), August 1974, pp. 1849-72.

Methods for Identifying and Evaluating the Nature and Extent of Non Point Sources of Pollutants, EPA, Washington, D.C., 1973.

Bryan, Edward H., "Quality of Storm Water Drainage from Urban Land," WRB, 8(3), June, 1972.

Hyphen (-) means data unavailable.

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* Standard Secondary Treatment, 60% P Removal, 85% BOD Removal, 50% Nitrification.

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reported in pounds of pollutant per acre per year. Data are commonly reported in the literature in terms of concentrations of pollutants. These data are difficult to interpret meaningfully without knowledge of the runoff quantities involved; thus we have chosen to work with total loadings rather than concentrations. Where entries in Table 5-9 are blank, it should not be interpreted to mean that the particular pollutant is not produced by the associated land use but rather that the data were not available.

It can be seen that urban runoff produces about the same order of magnitude of pollutant as secondary effluent from separately treated sanitary sewage, with the exception that it is somewhat lower in total nitrogen and higher in sediment. The implication of this result is that the attainment of ambient water quality standards in many areas will require a combination of land use management and higher treatment levels for point sources.

As indicated in Table 5-9, sediment loadings from construction activities may be as much as one order of magnitude greater than from other land uses. Thus even if this activity is confined to a small area of a watershed, it can significantly alter sediment yield.

Although the data in Table 5-9 are appropriate for order of magnitude analysis, they should not be regarded as useful emission factors. To qualify for use, emission factors for any particular region must be based upon knowledge of local soil characteristics, topography, climate and other features.

Models for Quantity and Quality of Urban Runoff

Urban runoff models range from those that demand simple calculations and very aggregated data to those that demand extensive computer time and information. The information requirement increases as the models reflect more of the main processes which govern runoff: interception, evaporation, transpiration, infiltration, surface detention, overland flow, gutter flow and pipe flow. Empirical and mechanistic formulations have been used to simulate individual subprocesses. Only the computer revolution has made it possible explicitly to analyze such large and complicated systems in the level of detail and resolution suggested here.

Before we discuss our review of runoff models, we examine the few recurring formulations which have been used for calculation of runoff quality. These methods, which are related to (1) washoff and (2) erosion from impervious surface areas, are much less advanced than those used to calculate runoff quantity.

1. Washoff from Impervious Areas. Runoff is the crucial mechanism for the proliferation of stormwater pollution. The accuracy of prediction of three processes influences the quality of pollutographs and loadographs;* the processes are:

a. peak rate and total volume of runoff;

b. accumulation of pollutants on pervious and impervious areas; and

c. washoff and transport of pollutants by the runoff.

The following paragraphs describe formulations relevant for runoff quality. The problem in modeling the accumulation process of dust and dirt on impervious areas was identified when we described the existing data base for this process (see above). A simple model is used to map the accumulation of dirt and dust to runoff quality through the medium of runoff quantity.

Washoff and transport of pollutants by runoff are represented by a linear differential equation. It is assumed that the amount of pollutants washed off a street surface in any time interval is proportional to the amount of pollutants remaining on the street surface. EPA's SWMM** was the first program to include this model. In order to fit the equation to these purposes some assumptions are made; these are described below.

Because R, the runoff rate, effects the rate of pollutant removal, the so-called "runoff constant, K, in the differential equation must be at least loosely dependent on R. However, given two watersheds identical except for their areas, a higher runoff rate would occur from the larger watershed for the same rainfall rate on both. The areal effect can be lessened by dividing the runoff by the impervious area of the watershed. The impervious area is used because it is assumed that the amount of the runoff from the pervious area is negligible -- which might be quite incorrect for some soils under certain antecedent conditions. Since cfs per acre are equivalent to inches per hour,* it has been stated that the "runoff constant" is functionally dependent on the runoff rate R_I (inch/hour) from the impervious area. Finally, assuming that the constant is directly proportional to R_I, the functional form becomes $K = E_u R_I$ where E_u = urban washoff decay coefficient. The original formulation can be integrated over a time interval Δt during which R_I is constant to yield the rate of removal of mass from the watershed. The value of 4.6 for E_u is frequently cited and implies that a uniform rainfall of 1/2 inch per hour would wash away 90 percent of the pollutant in one hour. But not all the dust and dirt on the watershed can be washed off by the runoff at a given time t. That implies that all the pollutants tied to the dust and dirt are not available either. Again the data of EPA's SWMM** are generally cited as reasonable values to compute the available fraction, at any given time, for suspended solids, settleable solids, BOD, total nitrogen, orthophosphates and coliforms.

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* A loadograph is a graph of pollutant load as a function of time while a pollutograph is a graph of pollutant concentration as a function of time.

** Metcalf and Eddy, Inc., *et al.*, Vol. 1 to 4, Final Report, *op. cit.*

The simple simulation model of the washoff process described above appears to be the only presently existing predictor of water quality in overland flow.*** Roesner, et al.,† claim to have computed good results with this predictor while Colston†† claims the contrary.

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* $$\frac{\text{ft}^3}{\text{sec-acre}} * \frac{\text{acre}}{43{,}560\ \text{ft}^2} * \frac{12\ \text{in}}{\text{ft}} * \frac{3{,}600\ \text{sec}}{\text{hr}} = .9917\ \frac{\text{in}}{\text{hr}}$$

** Metcalf and Eddy, et al.

*** Sutherland and McCruen, op. cit., have recently presented a new formulation, predicting the removal percentage of total solids by different volumes of rain.

† L. A. Roesner, D. F. Kibler, and J. R. Monser, "Use of Storm Drainage Models in Urban Planning," presented at the AWRA, Urbana, Illinois, pp. 400-405 (1973).

†† N.V. Colston, "Pollution from Urban Land Runoff, "Water Resources Research Institute, U. of North Carolina, March 1974.

Unsatisfactory results could be calculated due to the inadequacy of the formulation as well as due to poor model calibration.

2. Erosion. The universal soil loss equation* is generally used to compute erosion as a function of factors of rainfall-erosion, soil erodibility slope length, slope gradient, cropping-management, and conservation practice. This equation has been considered the most useful because it reflects considerable data, especially east of the Rockies. However, one problem occuring mainly in the west has been in calculating the Wischmeier and Smith** rainfall erosion indices. This index is calculated by multiplying total kinetic energy of a given storm (foot-tons per acre) with maximal 30-minute rainfall intensity of the storm (inches/hour).

The kinetic energy of rainfall has been given empirically by Wischmeier and Smith*** and is dependent on the rainfall intensity. Therefore, in order to compute the total kinetic energy of a storm, information from recording raingage charts must be utilized. The kinetic energy for each intensity increment can be calculated and the result multiplied by the depth of rainfall at that rate. These partial products can be summed to yield the total kinetic energy for the storm (E). The annual rainfall-erosion factors for approximately 2,000 locations in the U.S. have been summarized and published in the form of "iso-erodent" maps.† Although the USDA Handbook was prepared for use in agricultural areas, the methodology and data can be used for estimating erosion in urban areas and at construction sites. If desired, rainfall-erosion factors can be applied which represent rainfall intensity for a specific storm such as the maximum intensity storm of record. Thus the factors are not limited to yearly averages. Simple empirical formulas have been attempted for estimating the rainfall-erosion index in the western states.*

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* "Rainfall-Erosion Losses from Cropland East of the Rocky Mountains," Agriculture Handbook No. 282, Government Printing Office, Washington, D.C., 1965.

** W. H. Wischmeier and D. D. Smith, "Rainfall Energy and Its Relationship to Soil Loss," Transactions of the American Geophysical Union, Vo. 39, No. 2, April, 1958, pp. 285-291.

*** W. H. Wischmeier and D. D. Smith, op. cit.

† U. S. Department of Agriculture, Agriculture Research Service, "Rainfall-Erosion Losses from Cropland East of the Rocky Mountains," U.S. Department of Agriculture, Agriculture Handbook No. 282, 1965.

The soil erodibility factor has been determined for most of the soils found in the U.S. and are available from the Soil Conservation Service. Way and Long,** for instance, reproduce a USDA graph of curves which relate the soil-loss ratio to slope length for gradients from 2 to 20 percent.

The additional necessary information can be found in SCS maps and through contact with SCS personnel.

Although the universal soil loss equation fits very well into a planning model, one must recognize that there are a number of difficulties in applying this equation in generalized land use planning. These difficulties include:

- finding good data for the rainfall-erosion index as well as for the erodibility index of certain soils;
- averaging of length and slope factors in complex topography;
- the equation has been established only to predict soil loss resulting from splash, sheet and rill erosion -- it is not supposed to deal with gully or streambank erosion, or with erosion from non-arable land;
- according to Williams and Berndt,*** the soil loss equation will overstate soil loss from land where

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* J. K. H. Ateshain, "Estimation of Rainfall Erosion Index," J. Irrigation and Drainage Div., ASCE, IR 3, September, 1974, pp. 293-307.

** D. Way and S. Long, "Soils: Appendix to Report on Year 2," National Science Foundation Study, Harvard Graduate School of Design, December, 1973.

*** J. R. Williams and H. D. Berndt, "Sediment Yield Computed With Universal Equation," J. Hydraulics Division, ASCE, 12/72, Vol. 98, No. HY12, pp. 2087-2098.

the slope is concave up, and understate it from land where the slope is concave down; a convex slope, if it exists, is an unstable condition and the slope of the side facing the stream or outfall should be used;

- if the grid system is too coarse, the interrelationship between factors might not be realized sufficiently. For instance, if the most erodible soil is not on the steeply sloped land, results might be different than if it is.

But many successful applications of the formula have been reported. Way and Long,* for instance, adapted the model to the Boston Southeast Sector. The rainfall-erosion factor, according to the USDA, is 130. They found the erodibility factor for three kinds of soils. They used cells of one hectare to calculate the slope-length factor.** Both the cover index factor, C, and the erosion control practice factor, P, were assumed equal to 1 (construction areas).***

The sediment delivery ratio (SDR) is an additional factor to be estimated in areawide modeling, in order to calculate the amount of sediment which finds its way into the receiving water body. This is an empirical coefficient and takes account of particle size, flow depth, land use, etc.

Considerable research is currently being performed in order to refine and extend the usefulness of the universal soil loss equation. Emphasis is being given (1) to assessing the effects of vegetative cover and management variables for largely undisturbed areas, such as forest and rangeland* and (2) to estimating the erodibility of soils and subsoils based on fundamental physical and chemical soil characteristics.** Williams*** modified the universal soil loss equation in order to improve its application for predicting storm sediment yields. He substituted the product of storm runoff volume and peak runoff rate for the rainfall energy factor. This modification should overcome the problem that there is no single-valued relation between sediment yield and a rainfall energy factor; thus it should be possible to obtain for identical rainfall amounts and intensities varying sediment yields if antecedent moisture conditions are not identical. Williams used 18 watersheds in Texas and Nebraska to test the modified equation. It explained 92% of the variation in sediment yields. But due to the limited application of this equation only the original equation has been introduced into the available computer packages up to now.

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* D. Way and S. Long, op. cit.

** One must remember that because of non-linearity, the number of segments into which the area is divided will influence the results.

*** P and C are the factors to be varied in order to evaluate the impact of construction.

These two mechanisms, washoff from impervious areas and erosion, were found in various runoff models which we investigated in some detail.* Table 5-10 characterizes some of these models:**

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* W. H. Wischmeier, "Estimating the Cover and Management Factor for Undisturbed Areas, _Purdue J._, pap. 4916, 1972.

** See, for example, W. H. Wischmeier and J. V. Mannering, "Relation of Soil Properties to Its Erodibility," _Soil Sci. Soc. Amer._, 33, pp. 131-137, 1969, and W. H. Wischmeier, C. B. Johnson, and B. V. Cross, "A Soil Erodibility Nomograph for Farmland and Construction Sites," _J. Soil Water Conservation_, Vol. 26, pp. 189-193, 1971.

*** J. R. Williams, "Sediment Yield Prediction with Universal Equation Using Runoff Energy Factor," paper presented at Sediment Yield Workshop, USDA Agriculture Resource Service, Oxford, Mississippi, Nov. 28-30, 1972.

- Model of URS Research Company (URS).***
- Model of Avco (Tulsa).†
- Model of University of Cincinnati (CURM).††
- Model of EPA (SWMM).†††
- Model of Road Research Laboratory Method (RRL).§

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* Working Paper No. 2, "Review and Analysis of Land Use and Water Quality: Concepts and Models of the Relationships," prepared for the Environmental Protection Agency under Contract No. 68-01-2622 by Meta Systems Inc, January, 1975. Only after most of our limited literature review was finished, an extensive review of conceptual models became known to us. A. Brandstetter, "Comparative Analysis of Urban Stormwater Models," Batelle Pacific Northwest Laboratories, Environmental Management Section, for U. S. Environmental Protection Agency, 1974.

** Abbreviations in parenthesis will be used for further characterization of the models.

*** "Water Quality Management Planning for Urban Runoff," URS Research Company for U. S. Environmental Protection Agency, Office of Water Planning and Standards, Contract No. 68-01-1846, August, 1974 (Draft).

† "Storm Water Pollution from Urban Land Activity," AVCO Economic Systems Corp., Final Report, Contract 14-12-187, FWQA, 1970.

†† C. Papadakis and H. C. Preul, University of Cincinnati Urban Runoff Model, J. Hydraulics Division, ASCE, Vol. 98 (HY10), October, 1972, pp. 1789-1804.

††† Metcalf and Eddy, et al. (op. cit.)

§ M. L. Terstriep and J. P. Stall, "Urban Runoff by Road Research Laboratory Method," J. Hydraulics Division, ASCE, 95, November, 1969, pp. 1809-1834.

Table 5-10

Comparison of Comprehensive Storm Water Management Models

Model	URS	TULSA	CURM	SWMM	RRL	LECLERC	STORM
Temporal Description of Event	Discrete	Discrete	Discrete	Discrete	Discrete	Discrete	Continuous (Discrete Poss)
Interception Evaporation Transpiration	Neglect	Neglect	Neglect	Neglect	Neglect	Neglect	Neglect
Depression Storage	Neglect	Neglect	Exponential Filling Rate	Fills before overland flow empirical assumptions	Neglect	Neglect	Empirical assumptions
Infiltration	Neglect (impervious)	loss factor	Horton	Horton	Neglect (impervious)	Horton w/constant parameters	implicit in runoff coefficient
Overland Flow	Time lag nomograph	Neglect	Profile with increasing depth (empirical rel.) MANNING	Kinematic wave equation	Linear Time-Area Routing	Kinematic wave equation	Mod. Rational Formula
Gutter flow		Neglect	Outflow = Σ inflows		Manning-Izzard		
Pipe Flow		Neglect	No storage routing/lagged; using average weighted velocity	storage routing Manning	storage routing; lagged using full bore velocity		
Surcharge	Neglect	Neglect	Neglect (gives indication)	stores (volume contin.)	increases pipe diameter	Neglect	Neglect

Table 5-10 (continued)

Comparison of Comprehensive Storm Water Management Models

Model	URS	TULSA	CURM	SWMM	RRL	LECLERC	STORM
Data Needed	Land use type climatic antecedant slope; connected impervious main drainage length; storm event; pollution loading	land use antecedant street area environmental index (house, lot, parcel)	land use antecedant physiographic % impervious event; sewer network Manning's n	land use antecedant physiographic % impervious sewer network event; pollution loading Manning's n	land use terrain connected impervious length of main drainage; event Manning's n	See SWMM (also detailed map)	land use terrain runoff coeff. antecedant pollutant loading; erosion/rain record available storage and treatment
Pollutant Transformation	all of them	five categories	-	12 pollutants BOD, colif., SS, etc.	-	-	SS, settleable solids, BOD, N, PO_4 sediments
Output	hydrograph loadograph pollutograph	pollutant load runoff (regression)	hydrograph	hydrograph pollutograph storage/treatment requirements erosion	hydrograph	hydrograph	hydrographs pollutographs storage/treatment requirements erosion
Calibration Verification	None	None	Yes/Questionable	Yes/quantity okay; quality questionable	Yes/limited	Yes/questionable limited application	Yes/in process ↓

- Portion of MIT Catchment Model (Leclerc).*
- Model of Hydrologic Engineering Center, U. S. Corps of Engineers (STORM).**

The table is self-explanatory, so only a limited number of comments are made.

The first two studies (URS and Tulsa) are empirical and employ simple formulations. The three models which have been cited frequently in recent years have been CURM, SWMM and RRL. Literature discussions have presented comparisons among these models in order to establish the recognized superiority of one or another. Heeps and Mein*** presented an instructive comparison of the three models. It discusses a number of important factors such as different levels of aggregation, which influence model results, and is the only study of its type currently available. Another recent comparative study of the same models became known to us; it confirmed Heeps and Mein's results.† In general, SWMM is recognized as the model which gives the best results for small catchments (less than five square miles).

The model of Leclerc was developed as part of the overall MIT-catchment model. This part was selected for review because it was the most recent in a series of documents which refer to the MIT-catchment model, even though it is very complicated. In general, the MIT-catchment model is viewed as a good predictor of the runoff from large watersheds.*

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* G. Leclerc, "Methodology for Assessing the Potential Impact of Urban Development on Urban Runoff and the Relative Efficiency of Runoff Control Alternatives," Ph.D. Thesis, MIT, June, 1973.

** U. S. Corps of Engineers, "Urban Runoff: Storage, Treatment and Overflow Model, STORM," U. S. Army, Davis, California, Hydrologic Engineering Center, Computer Program 723-S8-L2520, May, 1974.

*** D. P. Heeps and R. G. Mein, "Independent Comparison of Three Urban Runoff Models," J. Hydraulics Division, ASCE, Vol. 100, HY7, July, 1974, pp. 995-1009.

† J. Marsalek, T. M. Dick, P. E. Wisner and W. G. Clarke, "Comparative Evaluation of Three Urban Runoff Models," Water Resources Bulletin, Vol. II, April, 1975 (No. 2), p. 306.

The last model examined in detail is the STORM model designed at the Hydrologic Engineering Center in California. Of the models we reviewed in detail, this is the only continuous one. It retains conditions due to previous storms and uses them as input for antecedent conditions of the present one. It uses an adjusted rational formula containing a composite runoff coefficient. In addition to a series of runoff hydrographs, it also produces a series of pollutographs for suspended solids, settleable solids, BOD, N, and PO_4, using formulations described above. STORM models storage-treatment requirements, if desired, and takes into account erosion by applying the universal soil loss equation. STORM has recently been recoded by Meta Systems such that coliforms (MPN) can also be used for characterization of runoff quality. It does not have any routing routines so that the application is limited to grid spacings of approximately 10 square miles. But the model could be modified through introduction of a simple time-area routing mechanism,** so that larger sub-basins could be simulated without a separate water quality routing model.

The necessary data consist of land use categories, terrain description, pollutant loading, runoff coefficients, antecedent conditions, available storage and treatment, erosion and a precipitation record. Non-urban and urban runoff are included; the resulting equations are basically the same. Non-urban runoff can be interpreted as urban runoff from a land-use category with negligible impervious area. Various types of outputs may be generated. The time interval, in the current version of the model, is one hour.

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* Brendan Harley, Presentation on Urban Runoff Models, BSCE/ASCE -- Meeting, April 8, 1975.

** See, for example, the method applied by O. Lindholm, Modeling of Wastewater Disposal Systems, in: R. A. Deininger, (ed.), Models for Environmental Pollution Control, Ann Arbor Science, 1973.

Other Emissions and Interfaces with Water Quality

Beyond the point and non-point source emissions described above there are other sources of emissions which have a bearing on water quality. The following pages cover solid waste disposal, on-site wastewater disposal and other types of land use effects which impact water quality.

Solid Waste Aspects. Since solid waste has various implications for water quality, many of these implications are qualitatively recognized, but unfortunately have not been formulated in a functional way.

There is no consensus in the literature on the amount of solid waste generated in urban areas. This results from the scarcity of good samples as well as from the problem of discriminating between waste generation and waste collection rates. The collection rate from regular pick-ups is usually substituted for the generation rate because the sampling is done only on the collection rate. Communities have different regulations regarding the types of residential (and commercial) solid wastes eligible for regular collection vehicle pick-up. Actual practice depends heavily on the attitude of the collection crew. Five pounds per capita per day in an urban area has frequently been cited as a representative figure of the pick-up rate. But data recently collected by the Data Acquisition and Analysis System, Inc., for the Environmental Protection Agency Solid Waste Management Office indicate that five pounds per capita per day is far too high for residential areas.* Its figures, based on the per capita pick-up rates of 23 collection routes in five metropolitan areas during January and February, 1972, indicate 2.0 to 2.5 pounds per capita per day. But reliance on this average value might lead to inadequate policies due to high variances. For example, in a recent study in Springfield, Massachusetts,** the average value was found to be approximately 2.5 pounds per capita per day, but the data showed significant seasonal and spatial distribution with high coefficients of variation. The composition of the wastes also varied seasonally.

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* "Data Acquisition and Analysis System, Quarterly Report January-March, 1972," report by ACT Systems for Environmental Protection Agency, Solid Waste Management Office, April, 1972, Contract Nos. 69-03-0034 and 68-03-0097.

** P. M. Meier, J. Kühner, and R. Bolton, "Wet Systems for Residential Refuse Collection: A Case Study for Springfield, Massachusetts," Curran Associates, Inc. for Environmental Protection Agency, 1974, NTISB-PB-234-499.

These facts indicate the importance of considering a variety of events instead of a single event as the "planning event" in order to accommodate the spatial and temporal differences. Lower per capita collection rates in core cities, but greater potential for spillover* and thus greater pollution potential from heavy runoff (due to high degrees of imperviousness) have to be contrasted (or balanced) with higher collection rates per capita in suburban areas, but lower potential for spillover and thus lower peak pollution potential from runoff (due to higher perviousness). The seasonal significance of organic and nutrient impact on the suburban runoff quality from gardening and its wastes must also be considered in this light.

Some recent studies have attempted to derive aggregated estimation of the solid waste generation rate (i.e., demand rate for collection services) as a function of socio-economic factors.** The use of input-output analysis has been suggested to predict generation rates of industrial wastes on a regional basis.*** The number of employees, location, type of commercial firm, etc., have been applied as independent variables, to estimate rates of commercial solid waste generation.* It is difficult to find good approximation for the spillover rates from the collection of the various solid wastes, even though these rates would be of interest in determining the dust and dirt accumulation and its composition in impervious urban areas (see above).

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* Inadequate storage of wastes for pick-up in high-density living areas, stray dogs, rats, etc., lead to a high spilling rate in core cities; see, for example, Alan M. Beck, The Ecology of Stray Dogs, A Study of Free Ranging Urban Animals, Baltimore: York Press, 1973.

** See, for example, D. Grossman, J. F. Hudson, and D. H. Marks, "Waste Generation Models for Solid Waste Collection," Journal of Environmental Engineering Division, ASCE Vol. 100 (EE6), December, 1974, pp. 1219-1230. R. Bolton, in P. M. Meier, et al., op. cit.

*** H. I. Stern, "Regional Interindustry Solid Waste Forecasting Model," Journal of Environmental Engineering Division, ASCE, Vol. 99, December, 1973, pp. 851-872.

Relatively few studies have been done on the simultaneous estimation of composition and magnitude of solid waste as functions of socio-economic, seasonal and locational factors.** National averages are usually available. Some attempts have been made to estimate composition on a regional basis. These data are presented for comparison without considering yard waste.***

Further data collection will be necessary before all of the factors influencing waste generation are known and their interrelationships are specified. Unfortunately, data on seasonal variation of yard wastes (as well as of other components in cases of spills) are required to evaluate the impact on the quality of runoff. But seasonal fluctuations of solid waste composition are very seldom investigated and reported. The American Public Works Association cites some data from New York and Chicago (1939 and 1956, 1957 and 1958), but these seem to be out of date.† Hence, the necessity of making reasonable assumptions about the composition of solid waste and of its spilled portion remains with the analyst.

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* T. V. de Gueare and J. E. Ongerth, "Empirical Analysis of Commercial Solid Waste Generation," Journal of Sanitary Engineering Division, ASCE, Vol. 97, SA6, December, 1971, pp. 843-850.

** One study by the Environmental Protection Agency indicates that at least among low-income families, areas of multi-family dwellings may contribute less waste per capita (and, of different composition) than families in less dense, single-family structures: George R. Davidson, Jr., "Residential Solid Waste Generated in Low Income Areas," U. S. Environmental Protection Agency, Washington, D. C., 1972.

*** W. R. Niessen and J. Chansky, "The Nature of Municipal Solid Waste," ASME, Incinerator Division, 1969.

† See American Public Works Association, Refuse Collection Practice, Inter-State Printers and Publishers, Danville, 1967, p. 38.

In summary, the number and precision of formulations available for the generation of solid waste, including its magnitude and composition, are very limited. The relationship between generation and pick-up of solid waste is not well documented, nor is the influence of pick-up rates and methods on the accumulation of dust and dirt in urban areas However, it is necessary for the analyst to consider the quality of solid waste management in his estimation of dust and dirt accumulation.

Another important aspect is the potential danger of leaching from disposal areas. Recent reports, for example, from the Llangollen land disposal site in New Castle County, Delaware,* have confirmed the dangerous impact leaching might have on the quality of groundwater. The degree of pollution from solid waste disposal areas has been a focus of controversy for a long time. In recent years, several attempts have been made to provide quantitative information on the behavior of areas for land disposal of solid waste, to quantify the amount and composition of leachate,** and to develop specifications to control and/or prevent pollution. It is clear that as long as there is positive net infiltration (net infiltration = rain - runoff - evapotranspiration), leachate will eventually be produced by the solid waste disposal areas. The magnitude of infiltration depends on surface grading and drainage characteristics, surface treatment and planting of vegetation. The travel time to the bottom layer of the landfill depends on the water absorption capacity of the components in the waste. The type of subsurface then determines how much of the leachate finally reaches the groundwater. A bottom layer of clay might essentially seal the disposal area from the groundwater. The use of plastic liners as bottom layers would have a similar effect.*** This technique requires that the bottom layer be above groundwater, in contrast to the frequent practice of uncontrolled disposal into areas with groundwater contact.

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* See comments of Environmental Protection Agency officials before a subcommittee of the Committee on the Environmental Pollution of the Committee on Public Works, U. S. Senate, July 17 and 18, 1974.

** Leachate is defined as a solution of the dissolved and finally suspended solid and microbial waste matter produced by the contact of water with decomposing solid wastes.

*** See: Anonymous, "Asphalt-Lined Gravel Pit Solves Disposal Problem," The American City, 89(6): 68, June, 1974.

The composition of the leachate that might reach the groundwater depends on the composition of the solid waste, on the soil type of the bottom layer, and on the depth to the groundwater. The rate of solution varies for different components of the waste.

Remson, et al.,* developed a moisture-routing procedure for unsaturated landfills. The model is for the one-dimensional downward vertical flow system. The equation of continuity is used for predicting the hydrologic performance of any soil and refuse layer. Thus the physical system is an initial and boundary value problem. The uppermost or cover soil layer obtains moisture by precipitation and loses moisture by evapotranspiration and downward drainage. In underlying layers, moisture is added by drainage from overlying layers. From there it moves to still lower layers or is reduced by evapotranspiration if roots penetrate to, or almost to, the layer. The landfill's hydraulic characteristics have to be determined by experiments or comparison to similar materials whose characteristics are tabulated. Thus the model pays attention to the content, spatial distribution and time variation of moisture by calculating the available storage capacity** of each soil and refuse layer. The routing model has not been extended to include the quality aspects of leaching.

In order to evaluate the potential of pollution from landfills, various studies have attempted to simulate landfills under laboratory conditions by using different soil types, infiltration rates and waste compositions.*** Only a very few field data exist. Rovers and Farquhar* tried in a semi-natural environment (cylindrical cells buried in a landfill) to investigate the impact of variations in infiltration (such as seasonal changes) on composition and production rates of leachate and gas. They observed a linear relationship between the amount of material extracted per ton of residential solid waste and the specific volume of liquid movement through the refuse in inches per foot in similar densities. The amount of leachate produced, and its chemical and physical characteristics, varied seasonally with changes in the amount of infiltration. Leachate strength (as reflected by COD, $N\text{-}NH_3$, N-ORG, Ca, Mg, Fe and Cl) increased rapidly with an abrupt increase in infiltration. Alkalinity and pH decreased. These data are not conclusive, but it is possible to utilize them as an estimate of the most significant impact in cases of similar conditions. But it seems impossible at this time to build a general model to quantify the impact on the aquatic environment of existing or phased-out landfills due to the lack of data. No leachate should reach the groundwater (in case of impermeable bottom layers) from new landfills, or the quality of the leachate should be improved by self-purification during the vertical movement to the groundwater, such that its impact is negligible. The majority of states has introduced regulations which should assure proper construction and operation of new landfills. We suggest neglecting the direct impact of solid waste disposal areas on the aquatic environment in the set-up of the model chain, because the main pollution potential, namely leachate from existing and phased-out landfills, cannot be assessed due to the present lack of data on the spatial and temporal distribution of the quantity and quality of leachate and because modeling of the impact of pollution sources such as leachate, on groundwater quality seems rather impossible (see below) at present.

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* I. Remson, A. A. Fungaroli, and A. W. Lawrence, "Water Movement in an Unsaturated Sanitary Landfill," J. Sanitary Engineering Division, ASCE, SA2, April, 1968.

** Available water is defined as a moisture range between field capacity and the permanent wilting percentage, or initial moisture (whichever is greater).

*** A. A. Fungaroli and R. L. Steiner, "Laboratory Study of the Behavior of the Sanitary Landfill," J. Water Pollution Control Federation, February, 1971; S. R. Quasim and J. C. Burchinal, "Leaching from Simulated Landfills," J. Water Pollution Control Federation, January, 1970, pp. 371-379; and R . Helmer, "Menge und Zusammensetzung von Sickerwässern aus Deponien verschiedener Abfallstoffe," Müll und Abfall, 3, 1974.

Aspects of On-Site Wastewater Disposal Systems. Most of the modeling effort for on-site wastewater disposal has concerned the engineered, economic design of septic tanks as pre-treatment devices and subsurface soil-absorption fields* as disposal devices. Over many decades there have evolved design rules based principally on balancing the objective of returning the transporting water to the environment (principally by dispersal to the groundwater and evapotranspiration)** and that of containing potentially harmful organisms. The poorly understood mechanisms involved have led to imposing minimal distances between soil-absorption fields and wells used for drinking water supply. Such design rules and constraints are the consequences of empirical observation; at the present time they cannot be related to measures of environmental quality.

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* F. A. Rovers and G. Farquhar, "Infiltration and Landfill Behavior," J. Environmental Engineering Division, ASCE, Vol. 99, October, 1973, pp. 671-690.

Patterson, _et al_.*** have prepared a useful literature review pertaining to septic tanks and soil absorption fields. Kaufman† reviewed the chemical pollution of groundwater, including that due to septic tanks and soil absorption fields. Increasingly data are being accumulated on a case-by-case basis. For the most part such studies are rather anecdotal in nature. Little in the way of generalization appears possible.

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* Usually in the form of shallow trenches or beds, or deeper pits.

** Designs for long-term acceptance of septic-tank effluents are usually based on short-term fresh water percolation tests; see _Manual of Septic-Tank Practice_, U. S. Public Health Service, 1957.

*** J. W. Patterson, R. A. Minear, and T. Nedved, "Septic Tanks and the Environment," Illinois Institute for Environmental Quality, June, 1971, National Technical Information Service, No. PB-204 519.

† W. J. Kaufman, "Chemical Pollution of Ground Waters," _J. American Water Works_, Vol. 66, pp. 152-159, 1974.

Specific pollutants are being studied.* However, the literature often contains simplistic remarks of doubtful generality such as, "Where excessive number of septic-tank tile fields are found, especially in water-logged soils, detergents may still persist over considerable distances." Freundlich isotherms have been applied** for prediction of ammonia nitrogen, phosphate, and ABS. Unfortunately, for the most part these isotherms have concerned laboratory soil columns, containing such soils as Zimmerman Sand, Hayden Silt, or Milaca Clay. Therefore, it is not immediately clear that these formulations will be useful in the near future.

For some regions the SCS publishes maps showing where on-site wastewater disposal should not be attempted. These restrictions are based on judgmental factors developed by experts who take into account soil type, drainage conditions, topography, depth to bedrock and groundwater, etc. SCS studies in Connecticut* have been made, intending to relate such judgmental factors with the anticipated longevity of a system.

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* S. A. Klein, "The Fate of Detergents in Septic Tank Systems and Oxidation Ponds," Sanitary Engineering Research Laboratory, SERL Report No. 64-1, University of California, Berkeley, 1964.

S. A. Klein and P. H. McGauhey, "Effects of LAS on the Quality of Wastewater Effluents," Sanitary Engineering Research Laboratory, SERL Report No. 66-5, University of California, Berkeley, 1966.

S. A. Klein, "The Fate of Carboxymethyloxysuccinate in Septic-Tank and Oxidation Pond Systems," Sanitary Engineering Research Laboratory, SERL Report No. 72-10, University of California, Berkeley, 1972.

S. A. Klein, "The Fate of NTA in Septic-Tank and Oxidation Pond Systems," Sanitary Engineering Research Laboratory, SERL Report No. 71-4, University of California, Berkeley, 1971.

H. C. Preul, "Contaminants in Ground Water near Waste Stabilization Ponds," J. Water Pollution Control Federation, Vol. 40, pp. 659-669, 1968.

H. C. Preul and G. J. Schroepfer, "Travel of Nitrogen in Soils," J. Water Pollution Control Federation, Vol. 40, pp. 30-48, 1968.

** H. C. Preul and G. J. Schroepfer, ibid.

Clearly, such results are not transferable to other areas. Thus the lack of a sound quantitative description of the potential impact of subsurface disposal systems on the groundwater quality becomes obvious.

Other Aspects. Today's knowledge of the way land use influences algae production, temperature, and toxic materials (including pesticides) in the receiving water body is quite vague. Recent research has shed some light on these areas** but has not advanced to such a state that a discussion on modeling within the overall land use/water quality system is justified here.***

Models for Transport, Dispersion and Assimilation

The final class of models reviewed in this section are those which handle the transport, dispersion and assimilation of waste in surface and groundwater.

Residuals of land use activities impact both surface water quality and groundwater quality. The progress toward development of groundwater related models for transport/

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* D. E. Hill and C. R. Frink, "Longevity of Septic Systems in Connecticut Soils," Connecticut Agricultural Station, Bulletin 747, June, 1974.

** For example, E. J. Pluhowski, "Urbanization and Its Effect on the Temperature of the Streams on Long Island, N. Y.," U. S. Geological Survey Professional Paper 627-D, 1970; or "A Conceptual Model for the Movement of Pesticides Through the Environment," Ecological Research Series, Environmental Protection Agency 660/3-74-024, December, 1974.

*** Some of these aspects were described in detail in Working Paper No. 2, January, 1975.

dispersion and assimilation of pollutants has been limited.* The impact on groundwater quality cannot be easily evaluated, because, first, the aquifer is characterized by a slow response to input changes, and second, today's knowledge of groundwater contamination from septic tanks, soil absorption fields, etc., is rather anecdotal in nature (see above). In the last years attempts, mainly of the U. S. Geological Survey, have been made to develop models reflecting behavior of pollutants in the groundwater. Bredehoeft and Pinder** presented a physical-chemical digital computer model for predicting mass-transport and dispersion of contaminants under the limiting assumptions that no chemical reactions take place. The same assumption is made in Konikow and Bredehoeft's model,*** which was developed to predict changes in dissolved solid concentrations in response to spatially and temporally varying hydrologic stresses. These models are complicated and numerically and computationally very burdensome. Other modeling efforts have been concentrating on various chemical reactions in groundwater.† In contrast to these progresses, no successful modeling of decay of organic matter has been reported. Within the framework developed here, the only models of interest are those capable of coupling mass-transport and dispersion, and chemical reactions. No such model has been successfully devised, calibrated, and verified up to now.

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* See B. W. Adrian et al., Groundwater Pollution, Independent Work Study, Department of Civil Engineering, MIT, January, 1973.

** J. D. Bredehoeft and G. F. Pinder, "Mass Transport in Flowing Groundwater," Water Resources Research, Vol. 9, No. 1, p. 134-210, February, 1973.

*** L. Konikow and J. D. Bredehoeft, "Modeling Flow and Chemical Quality Changes in An Irrigated Stream-Aquifer System," Water Resources Research, Vol. 10, No. 3, pp. 546-562, June, 1974.

† See, for example, L. N. Plummer, "Mixing of Sea Water with Calcium Carbonate Ground Water," Geological Society of America, Memoir 142, pp. 219-236, 1975; other research has been concentrated on describing and programming the reactions of dissolution and precipitation.

Therefore we limit our discussion to surface water quality. The conceptual discussion above introduced the notion of a transfer function, a set of descriptive relationships which relate measures of emissions from point and non-point sources to measures of ambient quality. A set of transfer functions constitutes a water quality model.

It is beyond the scope of this paper to review the plethora of water quality models.* Rather, this section briefly reviews approaches and mathematical formulations that can be utilized as the descriptive transfer function for water quality measures.

Choice is often narrowed to two practical approaches to transfer functions for the development of a descriptive model of water quality management analysis. On the basis of careful examination of the characteristics of, and data availability within, the basin, the flow system is divided into a series of compartments. Each compartment is regarded as a continuous flow reactor within which biological culture is promoted by incessant input of energy and materials. The output (or more precisely, the state) is a consequence of complex physical, chemical and biological reaction on the input. Values of parameters and variables describing the compartment are approximately uniform and can be well represented by unique values. In other words, a parameter value everywhere in the reactor is about the same and can be lumped into a single, unique value. As a result of this space-wise lumping the dynamics of the state can be represented by a system of ordinary differential equations. If equations so obtained for all compartments are solved simultaneously (or sequentially in a straight-run river), a complete picture of the state (or water quality condition) is obtained. In most cases, a computer is used in deriving solutions. Figure 5-2 gives an example of simulated results for a simple stream system. The state is given as a scalar. Notice on the left, the value of the state variable in each compartment is uniform for any time t and that the profile consists of rectangular steps. The state of compartment i as a function of time is shown on the right; it

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* For a discussion of the evolution of sanitary engineering analysis leading to these models, see: H. A. Thomas, Jr., "Waste Disposal in Natural Waterways," in Models for Managing Regional Water Quality, R. Dorfman, H. Jacoby and H. A. Thomas, Jr., eds., Harvard University Press, Cambridge, Massachusetts, 1972.

Figure 5-2

Results of Lumped Parameter Approach

for Simple Stream System

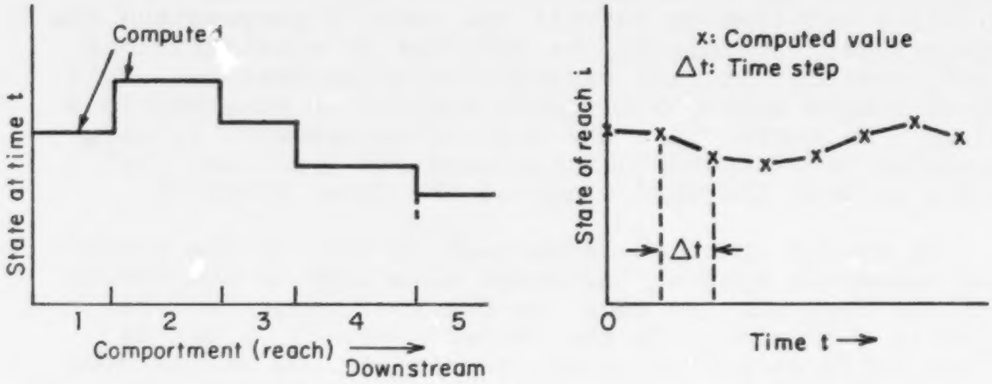
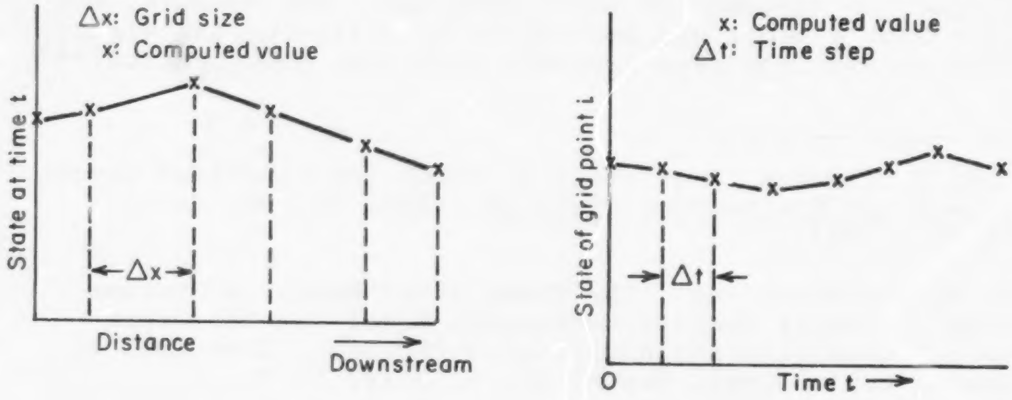

Computed
State at time t
1
2
3
4
5
Comportment (reach)
Downstream
x: Computed value
Δt: Time step
State of reach i
Δt
0
Time t

Figure 5-3

Results of Distributed Parameter Approach

for a Simple Stream System


Δx: Grid size
x: Computed value
State at time t
Δx
Distance
Downstream
x: Computed value
Δt: Time step
State of grid point i
Δt
0
Time t

consists of continuous line segments linking computed points. The contrast between the discontinuous steps on the left and continuous lines on the right is caused by lumping performance in space but not in time. In model-building an important accuracy problem often develops with regard to lumping: the size (length) of reach (compartment) is important. It is a compromise between the degree of resolution required to fulfill the model's purpose and its computational feasibility, in addition to considerations of data availability and variability of parameters. This kind of lumped approach has been applied in many previous studies. In particular, the well-known Delaware Estuary Comprehensive Study has demonstrated its applicability* as well as Meta Systems' study of the Tiber River.**

The second approach often used is that of the distributed parameter system. Although this lies in the domain of Eulean analysis, as does the previous one, they are logically different. In the latter approach, a set of partial differential equations represents the system dynamics. These equations are obtained from a limiting process by allowing the size of compartments to become infinitesimal. The equations so obtained represent the state at points but not in reaches (or at nodes, but not along arcs). Therefore, solutions of the equations must be interpreted accordingly. In deriving solutions, a river system is discretized and numerical approximations used to replace derivatives. Convergence and stability criteria play an important role in determination of grid size. Figure 5-3 shows an example of solution for a single stream system. The diagrams on the left of Figures 5-2 and 5-3 show the distinction between the two approaches. For example, the Saint John's model has been built by following the distributed parameter system approach with some modification.***

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* R. V. Thomann, "Mathematical Model for Dissolved Oxygen," J. Sanitary Engineering Division, ASCE, 85, No. SA 5, October, 1963.

** Meta Systems Inc, "The Tiber River Basin, A Systems Study: A Water Quality Management Model for the Tiber Basin," Consiglio Nazionale delle Ricerche, Institute di Ricerca sulle Acque, Report No. 5, July, 1973.

*** R. J. deLucia, E. A. McBean and J. J. Harrington, "System Optimization in the Saint John River," presented at the International Symposium on Applications of Computers and Operations Research to Problems of World Concern, Washington, D. C., August 20-22, 1973.

Some of the models developed limit their focus to the BOD/DO, residual/indicator couple while others examine a variety of conservative and non-conservative residual/indicator couples.* But the characteristics and capabilities of available models differ also in a number of other areas. These include the specificity with which they treat point versus non-point sources, the time frame of analysis, whether they use a steady-state or a non-steady-state approach, etc.**

In general, there are many well-developed physical/chemical water quality models available to predict the transformation of loads to instream quality. These are often of a higher degree of resolution and detail than are the models to estimate the loads as a function of land use. Aquatic ecological models are less developed than the physical/chemical water quality models; and ecological models which include both terrestrial and littoral grass systems as well as aquatic systems have only very limited development. The latter type of model is necessary to examine questions concerning the primary productivity/secondary productivity system in systems with significant wetlands. And the presence of wetlands can markedly effect the nutrient pathways in the food web and ultimately the biological indicators of water quality and level of secondary productivity.***

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* W. Chen and G. T. Orlob, "Ecologic Simulation for Aquatic Environments," Final Report to the Office of Water Resources Research, Water Resources Engineers, December, 1972.

** The most known non-steady-state model is the receiving water body module of the Environmental Protection Agency's SWMM; it was developed from those models which were capable of investigating tidal waters. The software of the module was recently revised and is available from EPA; see: W. C. Huber *et al*., *Storm Water Management Model; User's Manual, Version II*, *University of Florida for Environmental Protection Agency*, Project No. R-802411, March, 1975.

*** A "preliminary model" considering such relationships is presented in Appendix 3, "Ecological and Water Quality Constraints" in *An Operational Framework for Coastal Zone Management Planning*, Meta Systems Inc, *op*. *cit*.

Models Developed and Selected

Based on the review of literature and existing programmed models, we decided to develop models in some areas for which no appropriate models were available and to select several existing, programmed models to be used conjunctively to fill other needs. The review showed that the lack of models describing all the small subsystems of the urban land use/water quality relationship does not permit disaggregation to the degree of detail described in Figure 5-1. It rather seems appropriate to choose a coarser degree of aggregation and to group the existing models into the following subsystems: residual generation, collection, emission, transport/dispersion and assimilation (Figure 5-4).

There are models appropriate for our purposes for some of these subsystems. For other subsystems such models are non-existent. Models of residual generation, for instance, are not very well understood; they are frequently combined with models describing emission. Sometimes residual generation mechanisms are replaced by constant values; for example, models to be used for computing the washoff load contain dust and dirt accumulation rates which are treated as constant values per land use type instead of being functionally related to the land use dependent mechanisms which cause the dust and dirt accumulation. Estimates of residual generation of stationary land use sources are also largely based on "rules of thumb" rather than actual models. We did not find for our purposes any appropriate models which describe the collection of wastewater or stormwater. There exist some models for estimating runoff and washoff rates from storm events over a certain time period which fit our purposes, even though certain assumptions such as constant accumulation rates prevent a logic structure which spans the total land use/stormwater runoff/water quality relationship (see Figure 5-1). Models describing transport, dispersion, and assimilation are frequently used and well developed. Steady-state models are the most common, but there are also models which are capable of simulating the non-steady-state conditions due to time dependent variable input (such as stormwater runoff).

In order to develop efficiently the necessary computer software -- within available resources -- we have devised

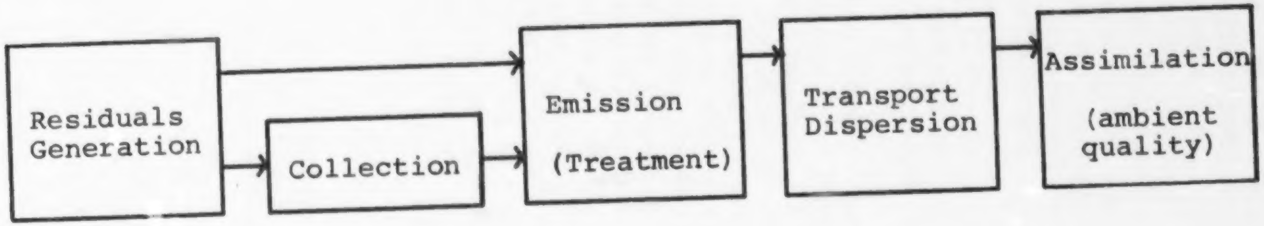
Residuals Generation
Collection
Emission
(Treatment)
Transport Dispersion
Assimilation
(ambient quality)

Figure 5-4: Scheme of Land Use Water Quality Relationship

two separate computing modules:* first, a module consisting of the subsystems of generation, collection, treatment, and emission of sanitary wastewater; and second, a module consisting of the subsystems of (aereal) emission (runoff, washoff and erosion) and of transport/dispersion and assimilation. The former represents our framework for the analysis of "treatment and discharge" of sanitary wastewater. The latter makes up our framework of analysis of the impact of intermittent urban stormwater discharges on water quality; it is composed of a modified version of STORM, a continuous model of the rainfall/land use/runoff relationship (see above), which was linked to the receiving water body module of SWMM, a dynamic water quality model.**

Our first framework is mainly designed to evaluate the hydraulic load of sewer and treatment systems, to compute the rates of utilization, and to indicate potential points of overutilization where relief strategies are needed. In neglecting the pollutants in the effluent, we have implicitly assumed that effluent standards are met.*** The actual impact of these discharges on the water quality of the receiving water body is considered by superimposing a constant effluent and its assumed quality from the treatment plants with the time dependent flow of stormwater. SWMM could have been used for an independent evaluation of wastewater discharge.† In the second framework emphasis was put on the impact of stormwater pollution on the receiving water quality rather than on evaluating the hydraulic capacity of stormwater related infrastructure. It has been implied for now that construction of additional large-scale downstream infrastructure to accommodate increased upstream runoff can be avoided; this means that upstream measures are applied which insure that the peak flow in the system does not increase beyond the present estimation. Developing a module to evaluate stormwater drainage capacity in a manner similar to the sanitary sewer capacity evaluation module is very complicated due to the large number of potential relief strategies (e.g., detention and retention ponds, surcharging, reuse, etc.) and their combinations. Therefore, it was decided to concentrate solely on the question of impact of stormwater on the receiving water body.

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* We discriminate between conceptual subsystems we have talked about up to now, and computing modules which make up the software for one or more of the subsystems at a time.

** See W. C. Huber, et al., op. cit.

*** It is feasible to devise a module which computes the quality of the treatment effluent, but it would not have added anything to the analysis at the time.

† Clearly the use of a steady-state model for this type of analysis would be more appropriate than a non-steady-state model, which uses up considerable computing time to reach a point of stabilization. We have neglected the steady-state analysis in our project, since it would have required considerable resources without adding anything new.

The sanitary sewer and wastewater treatment plant capacity evaluation module has been tested only for an artificial example, while testing of the linkage module has been tuned to the Hamden/Connecticut area and the Mill River Basin, in so far as appropriate data were available. This area and the existing data are discussed in Appendix A.

Sanitary Sewer and Wastewater Treatment Plant Capacity Evaluation Module.

At present, in order for the planner to obtain data concerning the overall performance of an area's sewer system assuming various population projections and development patterns, detailed studies must be performed for each projection, usually at a high cost of time and money. These costs significantly limit the capability of the planner to fully examine the impacts of the projections, and thus impair his ability to make more complete final recommendations.

To at least partially fill this gap, a capacity evaluation module of the relevant infrastructure was designed to provide the means with which a planner can obtain an estimate of capacity utilization of the larger sewer pipes at points throughout the system by using existing and projected land use patterns and population data. The module is designed so as to allow for a performance comparison of the existing sewer system against the present (time T), and a range of scenarios that may be projected for 10, 25, and 50 years into the future. The final output of the model consists of the actual flow, percent utilization and cumulative overflows for each sewer pipe as well as flow and utilization of the treatment plant. Once these results are examined, hypothetical new links and relief interceptors may be added to the existing system and the system's performance can again be checked against the projected scenarios. This process can be repeated until the system reaches a desired state of flow design and capacity utilization, or until it becomes clear that a feasible solution does not exist. It is hoped that through these capacity estimates the planner would be alerted earlier and more thoroughly to potential wastewater drainage problems under a wide range of projected or anticipated conditions.

The approach incorporated in the module enables the planner, with few constraints, to:

a. Define only those pipes of the sewer system -- to be called links -- he wishes included in the analysis, and

b. Take advantage of existing data by defining and dividing the area under study into subdivisions -- to be called cells -- that conform to the simplest form of data collection.

In the paragraphs below we briefly outline the model structure.* A tree network of links which are to be monitored has to be sketched on a base map of the area under study. This network will generally consist of sub- and feeder mains, trunk lines and final interceptors. Then a grid system of cells must be overlaid on this map. The cells need not be of any uniform or fixed geometry, but should be defined to facilitate the collection of data concerning the population and population equivalents which are required for each grid cell. It is assumed that the total wastewater generated within a cell is uniformly distributed throughout that cell. Each link in the system is assigned a percentage of the flow generated in the cell in which the link is located. The assigned flow drains into the link in a continuous, but not necessarily uniform, fashion, for the length of the link. On the basis of the above assumption, capacity checks will occur only at the downstream node of each link. Nothing is suggested concerning detailed layout and hydraulic design of relief sewers. This omission is based on the multiplicity of technical factors, many external to the module, which would play an important role in any such statement. When an overcapacity flow occurs, the planner, among the many choices, may select an independent branch of links, or a relief interceptor. In either case the technical assistance of a sanitary wastewater engineer will be needed to help determine exact location, pipe diameters, minimal velocity requirements, and other characteristics.

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* Details of the development of the module are described in Working Paper No. 4, "Progress Toward Synthesis and Integration of Land Use and Environmental Quality," prepared for the Environmental Protection Agency under Contract No. 68-01-2622 by Meta Systems Inc, June, 1975.

The following data should be collected:

1. Link characteristics, such as identification number, diameter in inches, length in feet, slope (feet per 1,000 feet), roughness coefficient, and an infiltration coefficient -- in gpd/inch diameter/mile.
2. The total population or population equivalents for the land use types under consideration.*
3. The expected wastewater generation in gallons per capita per day by land use.
4. Percentage of cell wastewater allocated to each link.
5. The type of unit, treatment plant or pumping station and its capacity in CFS and receiving flows from the terminal link.

A flow chart (Figure 5-5) indicates the logic of the program.

A sample output of results to be anticipated from the module is found in Table 5-11.** The maximum capacity of the sewer network and of the waste treatment plant are compared to the actual utilization at various future points in

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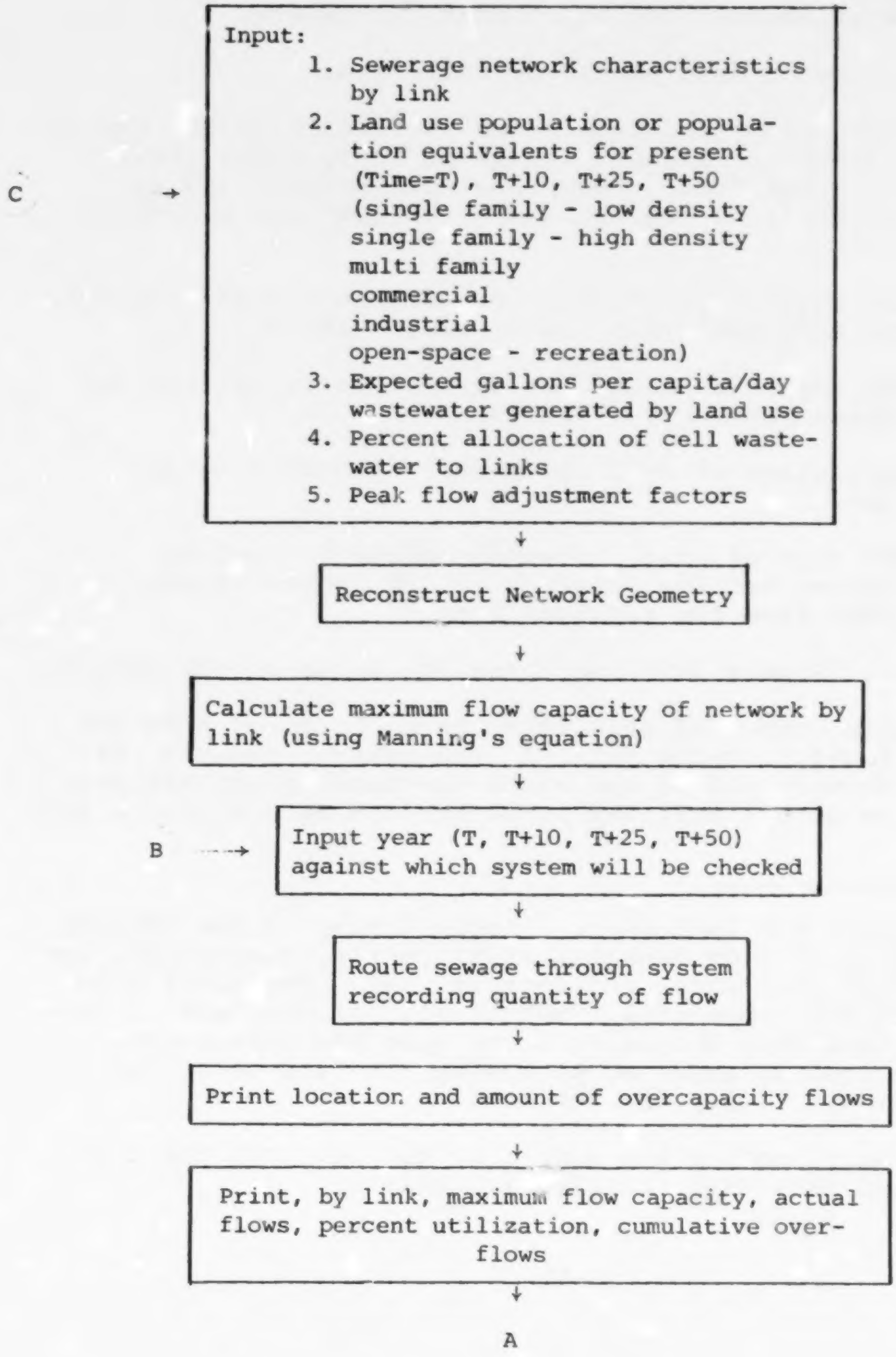
* We consider six land uses: single family -- low density, single family -- high density, multi-family, commercial, industrial, and open-space and recreational. The population equivalents for commercial, industrial, and open-space, recreational land uses should be based upon the wastewater flow value (gpc/d) assigned to one of the land uses; for example, single family low density.

** In order to reduce the number of tables, only three of the six land uses were included in Table 5-11.

Figure 5-5

Flow Chart

Sewer Routing Module



Input:

1. Sewerage network characteristics by link
2. Land use population or population equivalents for present (Time=T), T+10, T+25, T+50 (single family - low density
   single family - high density
   multi family
   commercial
   industrial
   open-space - recreation)
3. Expected gallons per capita/day wastewater generated by land use
4. Percent allocation of cell wastewater to links
5. Peak flow adjustment factors

Reconstruct Network Geometry

Calculate maximum flow capacity of network by link (using Manning's equation)

Input year (T, T+10, T+25, T+50) against which system will be checked

Route sewage through system recording quantity of flow

Print location and amount of overcapacity flows

Print, by link, maximum flow capacity, actual flows, percent utilization, cumulative overflows

Figure 5- 5 (continued)

Flow Chart

Sewer Routing Module

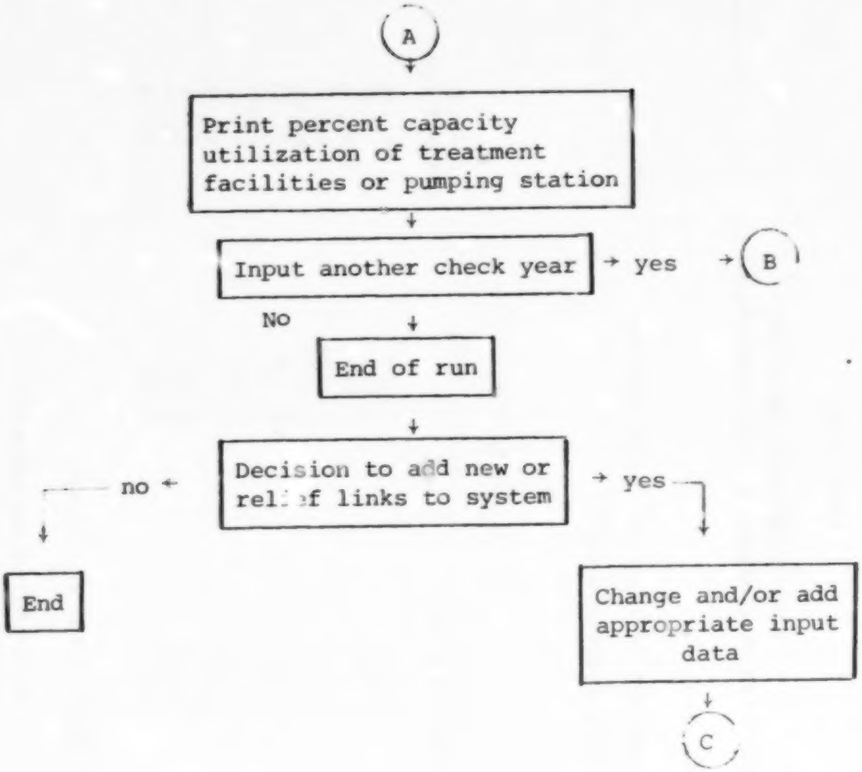

A
Print percent capacity utilization of treatment facilities or pumping station
Input another check year
yes
B
No
End of run
Decision to add new or relief links to system
no
yes
End
Change and/or add appropriate input data
C

Table 5-11

LINK CAPACITIES AND FLOWS

```
CHECKING SYSTEM CAPACITY FCR PROJECTED POPULATION  0 YEARS FROM PRESENT

FULL AND/OR OVERCAPACITY FLCWS

    LINK   6 FLOW EXCEEDED TFE MAXIMUM CAPACITY BY  12.69 PERCENT   (   1.577 CFS)

    THERE WERE   1 FULL AND/CR CVERCAPACITY FLOWS


                                   (FLOW VALUES IN CFS)

           LINK IC          MAXIMLM           ACTUAL FLOW         PERCENT          CUMULATIVE
                         FLOW CAPACITY                          UTILIZATION        OVER FLOWS

              1              1.203               1.114              92.61              0.0
              2              1.203               0.101               8.39              0.0
              3              1.957               1.533              78.35              0.0
              4              1.203               0.193              16.02              0.0
              5              1.2C3               1.023              85.00              0.0
              6             12.424              12.424             100.00              1.577
              7              5.769               1.354              23.47              0.0
              8             12.424               3.731              30.03              0.0
              9              1.203               0.514              42.73              0.0
             10              5.769               0.762              13.21              0.0
             11              3.548               0.761              21.44              0.0
             12              1.957               1.501              76.69              0.0

    TOTAL FLOW ENTERING TREATMENT PLANT (CFS) =    12.424

                              TREATMENT PLANT CAPACITY
                              ------------------------

                       STAGE          MAXIMUM          PERCENT
                                   CAPACITY (CFS)     UTILIZATION

                     PRIMARY          30.00             41.41
                     SECONDARY        20.00             62.12
                     TERTIARY         10.00            124.24
```

time; and overflow per network link as well as overutilization of the treatment plant are indicated. This mechanism permits the planner to assess the impact of an anticipated development pattern on specific cells (subareas) as well as on the total system. Changing the development scenario and then computing the associated utilization rates provides the planner with information which can be transformed to impact indicators relevant to the planning process (such as costs to be covered by local taxes). Overutilization of the capacity of the sewer network calls for relief sewers which can be built in various ways, while hydraulic overload of the treatment plant requires either capacity expansion or construction of an additional plant at a different location. The latter approach would be based on a concentration of overutilized sewers in a certain area and on a relief strategy which would advocate a separation of the sewer network into two independent parts.

In summary, this module allows for evaluation of the sewer and wastewater treatment capacity dependent upon the prevailing and future land use scenario and permits the planner to assess potential relief strategies. The dimensions of the necessary structures should then be passed on to the cost evaluation module (described in Section 6) to compute the associated costs and so to assess the physical as well as the financial and socio-economic impact of new development.

Linkage of Runoff and Water Quality Model

The second major module developed in the course of this work was the linkage of the urban runoff and water quality models. In contrast to the analysis of the impact of sanitary wastewater discharges from treatment plants, no generally accepted planning events such as a minimum average seven-consecutive-day flow once in ten years have evolved in the field of stormwater management. There does not exist any consensus as to which criterion to use to set the basic conditions: for example, a criterion involving both receiving water body flow and runoff or a joint recurrence interval for dry antecedent conditions, runoff, and receiving water body.* This is true for all intermittent discharges, for urban runoff as well as for discharges from non-point sources, such as agricultural or forestry areas. In our further discussions, however, we will emphasize urban runoff.

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* See J. Kühner and M. Shapiro, "Discussion of 'Urban Runoff Pollution Control State-of-the-Art'" (R. Field and J. A. Lager), J. Environmental Engineering Division, ASCE, 1976 (forthcoming).

A runoff model seems to be desirable which allows the planner to examine continuous records of storm and antecedent dry weather conditions, thus enabling him to identify critical events from these data, instead of using a model which can only handle a single rainfall event and therefore requires an a priori setting of the conditions to be evaluated. Another point of importance is the degree of temporal and spatial resolution of the model. Frequently the difference between the purposes of the model uses is poorly articulated, and there are suggestions that runoff models, for example, appropriate for detailed design problems be used in planning.

STORM, a continuous model, is attractive because of its relative simplicity of use. The data for which the model calls are not very detailed and seem to be available in most areas. The major drawback of the model is its simplified approach to the runoff coefficient, a coefficient on which much depends. This aspect of the model may be modified by choosing separate coefficients for each area; but ultimately, as in the cases of the other models, much reduces to subjective judgment in the choice of parameters. Appendix B summarizes some of our experimental runs concerning the sensitivity of the model to various parameters and assumptions.*

The model is designed to compute non-urban runoff and washoff in addition to urban runoff and washoff. The formulations pertinent to non-urban runoff are set up in the same way as for urban runoff, while washoff is based on emission rates rather than pollutant accummulation rates. Hydrographs and pollutographs are generated for every hour of runoff. No provision is made for variable time intervals of runoff generation.

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* Details of the model can be found in its manual, available from the Hydrologic Engineering Center, Davis, California; see U. S. Corps of Engineers, _op_. _cit_.

The hydrographs and pollutographs, generated by STORM for each sub-basin for certain rainfall events, have to be transferred to the non-steady-state water quality model,* in order to evaluate flow and pollution propagation in the receiving water. A computational link is required (see Figure 5-6).

The selected receiving water body module has two distinct phases (hydrodynamic and quality) which may be simulated together or separately. In the first phase the time history of stage, velocity, and flow is generated in the total system, while in the second phase these results are used to compute the concentration of conservative and nonconservative quality constituents.** The receiving water is divided into a series of discrete one- and two-dimensional elements which are the connections among nodal points. One-dimensional elements represent rivers and specific channels, and two-dimensional elements represent areas of continuous water surface. The velocity of flow is assumed constant with depth for each element. For each time-step, the equations of motion and continuity are applied to all nodes to derive the hydrodynamics for the system. The results are then used with equations for conservation of mass.

Various points have to be considered in the idealization of the physical system into one-dimensional (or channel) and two-dimensional (or area) discrete elements. The nodes are the points of constant inflow and/or outflow and of time dependent inflow and/or outflow. Being a non-steady-state model, SWMM does not have the capability to input runoff as a line source. Nodal points must have a minimum distance from each other in order to keep the numerical scheme stable. The dimensions of rectangular channels idealizing the river have to be chosen such that they reflect the real river dimensions to a large extent.

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* W. C. Huber, et al., op, cit.

** See Huber et al., op. cit., p. 269. Actually it turned out that we had to make some changes of the software, in order to run the phases separately. It is desirable to run these phases separately; the repeated use of the hydrodynamic routine would only use up enormous computing resources for the computation of the quality, where the hydrodynamic conditions are constant.

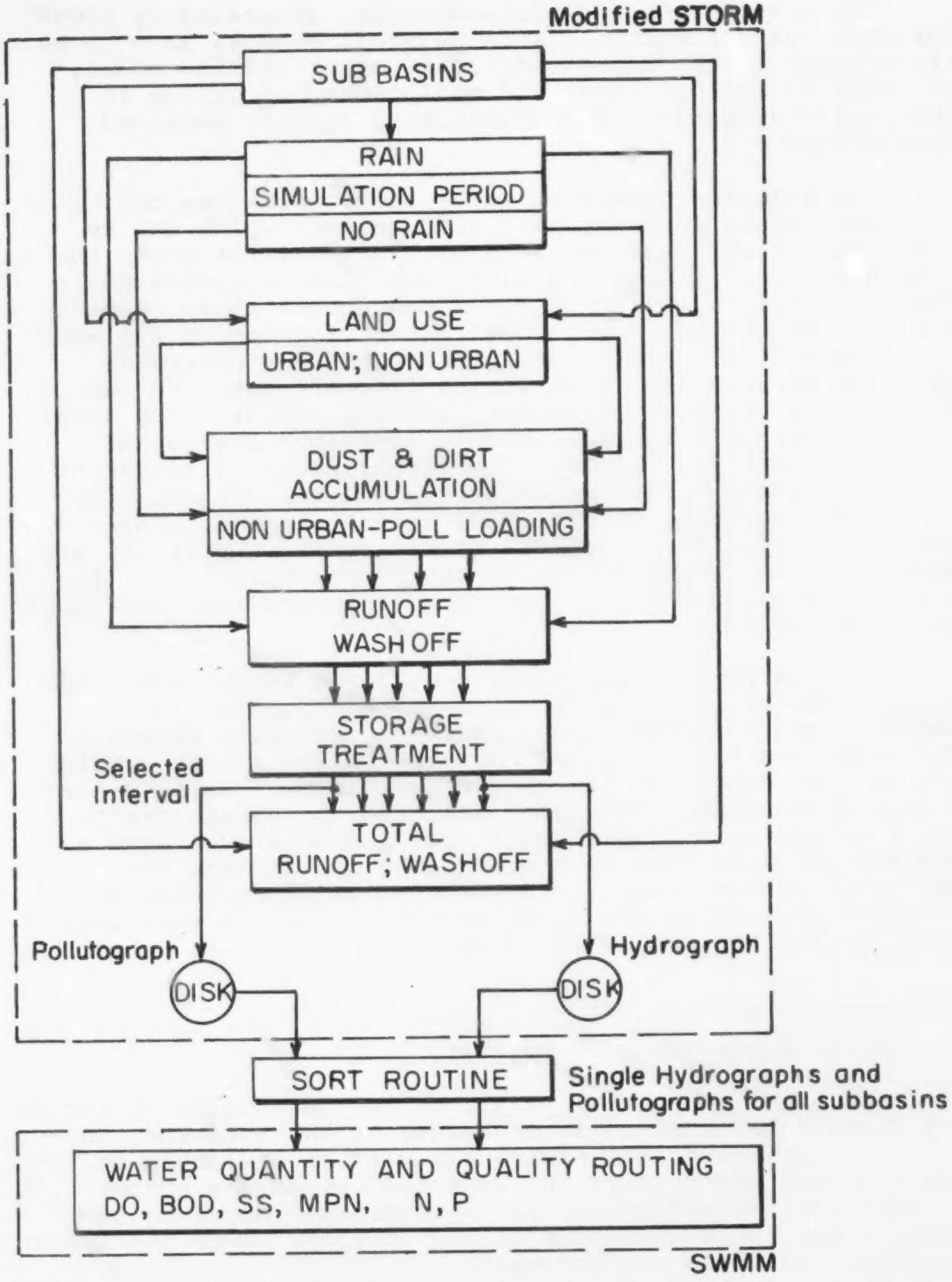
Modified STORM
SUB BASINS
RAIN
SIMULATION PERIOD
NO RAIN
LAND USE
URBAN; NON URBAN
DUST & DIRT ACCUMULATION
NON URBAN-POLL LOADING
RUNOFF WASH OFF
STORAGE TREATMENT
Selected Interval
TOTAL RUNOFF; WASHOFF
Pollutograph
Hydrograph
DISK
DISK
SORT ROUTINE
Single Hydrographs and Pollutographs for all subbasins
WATER QUANTITY AND QUALITY ROUTING
DO, BOD, SS, MPN, N, P
SWMM

Figure 5-6

Analysis Framework for Stormwater Runoff

This becomes particularly difficult when flow and quality of shallow rivers with wide floodplains have to be simulated. The introduction of some "storage nodes" or a "parallel channel" option might be of some help. In an urban setting, much runoff flows into the receiving water without being channeled through drainage systems; that means, that line-source type runoff has to be idealized into point discharges, entering at one of the nodes. Six conservative and nonconservative quality constituents can be handled by SWMM. The data requirements for this model do not exceed significantly the requirements that steady-state models of the same complexity (number of quality constituents to be modeled) show.*

When we attempted to link these two models (STORM and SWMM), whose computer programs (deck, listing and documentation) were available, various difficulties arose:**

1. STORM is a continuous model, while SWMM handles single events only. SWMM accepts the hydrographs and pollutographs of all discharge points for one rainfall event. Simulation of other intervals for which hydrographs and pollutographs are generated, should be performed subsequently. Thus, the hydrographs and pollutographs generated by STORM have to be stored on a discs and then handled individually by SWMM.*** The definition of events presented some difficulty because STORM defines internal events only when the rain event generates runoff. This is a major disadvantage because STORM can easily generate runoff in sub-basin 1 while not generating runoff in

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* How a calibration/verification exercise of the quality portion of such models could be done, has been discussed by Meta Systems at various occasions; see, for example, R. J. deLucia and T. Chi, "Water Quality Management Models: Specific Cases and Some Broader Observations," invited paper prepared for presentation at the World Health Organization, Government of Hungary Seminar on Systems Analysis in Water Quality Management, Budapest, Hungary, February, 1975.

** We discuss some details because a potential user, not well practiced in the application and linkage of large-scale models, frequently does not recognize the diversity of the problems encountered in linking such models.

*** Actually a routine could be developed to include the receiving water body module of SWMM in a loop of events.

sub-basin 2 for the same rain; the percentage imperviousness of the sub-basin decides the actual generation of runoff from rain. Thus, the notion of time intervals was introduced to control exogenously the rainfall runoff events of interest.

2. STORM's hierarchy of loops is watershed, event (time interval), timestep (of each single event), and pollutant, while SWMM's input is organized in the order of time interval (event),* timestep, pollutant, and watershed. Thus, a SORT-routine has to be used between the two modules to make the I/O routines compatible. A number of significant changes of input/output options had to be accomplished to make the linked model as flexible as possible.

Due to these arrangements, there are two points of interaction for the planner. First, he can choose the rain intervals (n) within the continuous simulation period of STORM which he wants to investigate; experience will permit the elimination of events of antecedent conditions and rainfall, which are of inferior significance. Then he can select those intervals (m) from STORM's output of pollutographs and hydrographs ($m \leq n$), which seem to have a major impact on the whole basin. This option permits him to reduce significantly the computing costs for analyzing only those intervals of interest to him. But it also allows the planner to simulate all the events if he desires to compute a frequency distribution of conditions which are of interest to his agency. Since the quality module of SWMM can be run without rerunning the quantity module, water quality computations can be done by varying pollutograph inputs generated for each point discharge of runoff. This fact also permits intensive testing of quality related parameters and thereby calibration of the quality module. The code has also been altered so that only quality constituents of interest have to be read from discs filled by STORM with six constituents.

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* Since SWMM considers only one event in its current version, this step would not have to be introduced in the hierarchy of loops in SWMM.

3. In calculating the quality of the runoff, SWMM's quality routine adds up the sediment load, calculated by the universal soil loss equation, and the amount of suspended solids, washed off the streets. The program performs this summation at every hour. In contrast, STORM does not link the two routines and hence does not sum up the two values. Actually, STORM only calculates the total value for the sediment load from each event. Thus, STORM's subroutine ERODE was reprogrammed in order to compute the sediment load for every hour of the rainfall-runoff event. Clearly, the total values per event are different for the two types of computations, because the rainfall-energy-relation is non-linear.* In case of relatively uniform rainfall intensities over the rain's duration, the values are quite similar; but if the rain shows strong peaks of intensity, the method of adding up hourly values yields higher total values. Since EPA's SWMM uses the universal soil loss equation on an hourly basis, we recoded STORM in the same way.

We have summarized most of the major changes made in the individual programs. This indicates the efforts which are necessary to link two models, whose programs are easily available and whose combined execution seems relatively easy (Table 5-12).

The value of this package is determined by the results it generates and the computations it permits (on the condition that the accuracy of the computations is satisfactory for the desired purposes). The combined models can be used in three basic ways depending upon the objectives of the analysis:

- Emphasis is on emissions: STORM is repeatedly executed without subsequent execution of SWMM;

- The impact of emissions (generated in each selected rainfall interval) on water quality of the receiving stream is of interest: STORM and SWMM are executed in series;

- Quality analysis under changing hydraulic and hydrologic conditions is of primary concern: SWMM is repeatedly executed without prior execution of STORM.

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* Wischmeyer, op. cit.

Table 5-12

Changes for an Efficient Linkage between STORM and SWMM

A. Changes in STORM

- Creation of $\genfrac{}{}{0pt}{}{H}{P}$ GPH* files to pass results from STORM to SWMM
- Use of rain interval instead of rain event for file generation
- Calculate erosion on hourly basis
- Accumulate erosion over the rain interval
- Add eroded material to suspended solids
- Add coliforms as sixth pollutant (in such way as it was done in SWMM's runoff and washoff module)
- Change output format for pollutants
- Calculate amount of dust and dirt, accumulated at the beginning of rain interval, as well as amount left over after rain event
- Modify input of land use data (acres instead of percentage)
- Frequent debugging of original program (logic, core, program, files, default)

B. Changes in SWMM

- Modification to accept $\genfrac{}{}{0pt}{}{H}{P}$ GPH as sequential input
- Write SORT routine to sequence $\genfrac{}{}{0pt}{}{H}{P}$ GPH input to be acceptable for SWMM
- Selection of one or more out of the six pollutants supplied in pollutograph
- Modify SWMM to run quality phase independently of hydrodynamics phase
- Introduction of weighting factors for $\genfrac{}{}{0pt}{}{H}{P}$ GPHs

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* $\genfrac{}{}{0pt}{}{H}{P}$ GPH means hydrograph and pollutograph.

For each use there exists a large number of possible combinations of input parameters and desired output. Appendix B provides some examples of possible computation with STORM, such as the evaluation of impact of land use patterns on emissions rates or different street sweeping strategies under use of different sweeping equipment. Exploring the ways that different future land uses in river sub-basins will affect the river's water quality requires a close interaction of STORM and SWMM. Appendix C contains a short summary of land use controls which can be compared by use of STORM and, subsequently, SWMM. STORM permits a comparison of the induced emission rates, while the hydrograph and pollutograph resulting from these land use controls allow for the evaluation of the impact of land use and environmental controls on the quality of the receiving water body. Altering dimensions of channels to reflect development of flow plains or conditions of constant flow and water quality, for example, gives room for an intensive study of the impact of time-dependent runoff. Problems such as the determination of various roughness coefficients for different flow situations can only be understood and solved by repeated runs with the hydrodynamic and quality portions of SWMM.

The following types of output can be generated by STORM and SWMM:

- the amount of every pollutant (total/year/sub-basin);
- the amount of every pollutant (total/rain interval/sub-basin);
- the hourly amount of every pollutant per sub-basin for specified rainfall intervals;
- the amount of dust and dirt on impervious areas at the beginning and end of rain intervals;
- total erosion for selected rainfall events and the amount finally reaching channels (stream) after application of a sediment delivery ratio;
- hydrograph (total/year/sub-basin);
- hydrograph (total/interval/sub-basin);
- hydrograph (total/hour/sub-basin);
- stage of water level at each selected node of the river system for every rainfall event;

- water level at every node of the river system for each day;

- velocity and flow in every channel of the river system for each day; and

- hourly concentration of selected pollutants at every selected node.

We have carried out some of the modeling combinations mentioned above and and have generated most of the possible output relevant to analysts; but we limit our presentation to a few examples. Appendix B contains a table of five rainfall events (Table B-1) which have been used for our test runs with STORM and which are also the basis for our computations here. In the following paragraphs we compare runs and their results in two ways: first, we compare the effects of various rainfall levels and base flows in the river on the quality of the receiving water body given the same land use; second, we compare the impacts of changing land uses under varying precipitation and base flow conditions. Factors considered in the comparison are pollutant and wave propagation in the receiving stream; superimposition of upstream waves and pollutants; accumulation and behavior of the pollutant in the lake; and actual differences resulting from different rainfall and flow conditions and changing land use patterns.

Results, discussed first, are based on the land use configuration of 1974 in the Mill River Basin; and later we will present results derived from the 1985 land use. Table 5-13 contains hydrographs of the first part of the rain interval 1 (January 21, 1974, 8 a.m. to 6 p.m.), as they are generated by STORM for the 11 sub-basins in the Mill River Basin for the 1974 land use conditions (Figure A-1 and Table A-6). Assuming that the precipitation is uniform over the whole river basin, the differences among the hydrographs indicate the varying sizes and degrees of urbanization of the sub-basins. Due to frequent precipitation in the time of the year represented in interval 1, a relatively high base flow was assumed in the Mill River; it is characterized by an accumulation to 215 cfs at the dam, the downstream point of the river system. Figure 5-7a* shows the change of the water level at the dam (junction 1) and Figure 5-8 at the point of inflow from the sub-basin Eaton Brook (junction

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* The ordinate of all Figures is "Depth in Feet" according to the definition in SWMM; it means distance from datum plane to water level.

Table 5-13

Hydrographs for All Junctions of the Mill River System (First Part of Rain Interval 1; Land Use 1974)

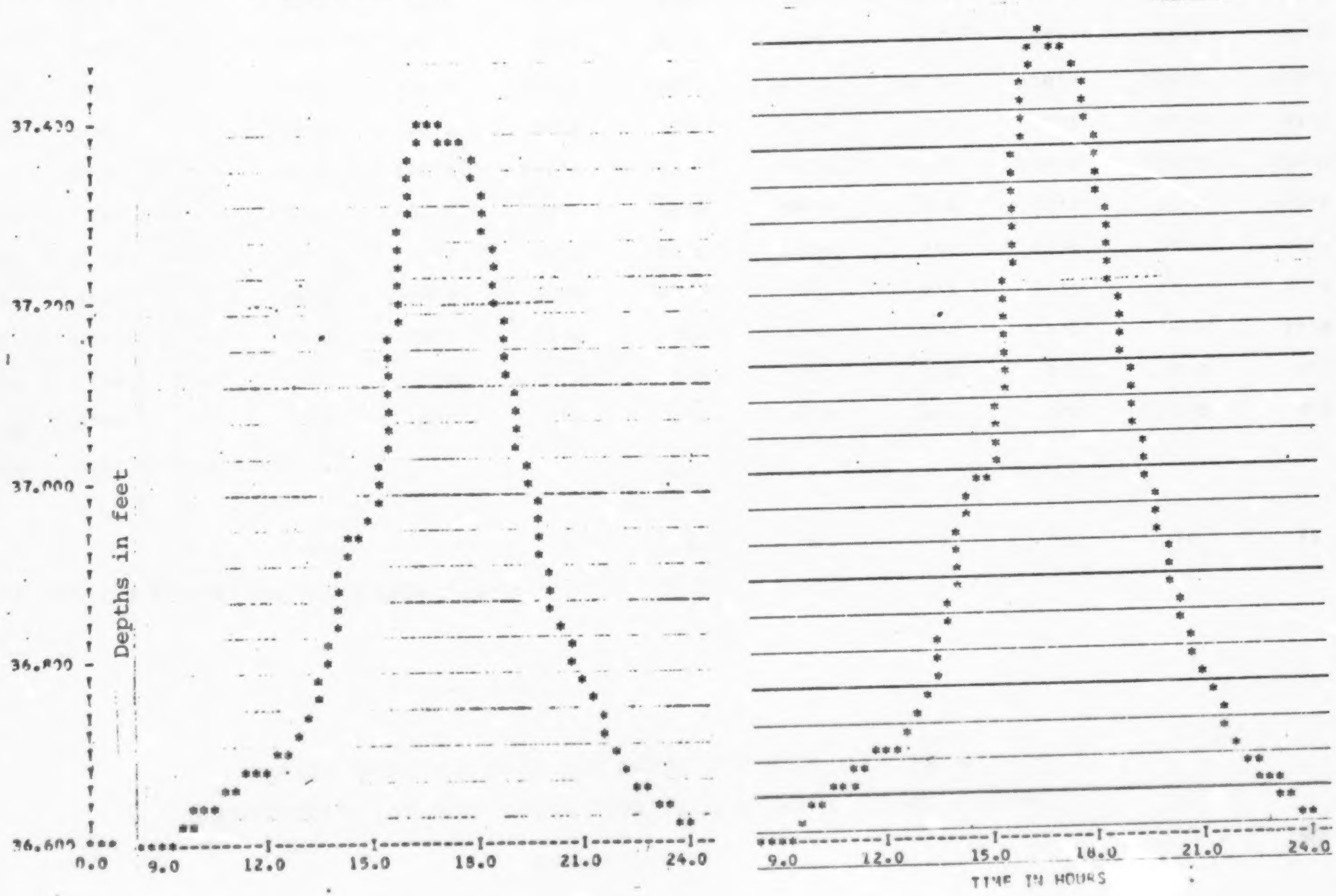
INPUT JUNCTION NUMBERS FOR FLCWS FRCM CARDS ARE:

TIME		2	4	5	6	7	8	9	10	11	12	13
HOURS	DAYS	VOLUME (CFS)										
8.0C	0.33	C.C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.C	0.0	C.0
9.00	0.38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	C.0
10.00	0.42	34.6	13.0	18.1	21.9	5.5	11.9	2.8	1.2	6.8	14.9	13.8
11.00	0.46	41.5	16.9	28.6	29.3	10.6	20.3	4.3	10.7	17.7	36.5	50.4
12.00	0.50	36.3	15.7	29.3	27.5	11.7	21.4	4.3	15.1	21.4	43.5	65.2
13.0C	0.54	48.4	20.9	39.1	36.6	15.6	28.6	5.8	20.1	28.6	58.1	87.0
14.00	0.58	187.7	80.9	151.7	141.9	60.6	110.8	22.5	78.0	110.8	225.0	337.C
15.00	0.63	72.7	31.3	58.7	54.9	23.4	42.9	8.7	30.2	42.9	87.1	130.5
16.00	0.67	43C.0	185.3	347.4	325.1	138.8	253.7	51.4	178.8	253.7	515.3	771.9
17.0C	0.71	54.5	23.5	44.0	41.2	17.6	32.2	6.5	22.7	32.2	65.3	97.8
18.00	0.75	42.4	18.3	34.3	32.0	13.7	25.0	5.1	17.6	25.0	50.8	76.1
19.00	0.79	C.C	0.0	C.C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	C.0

Figure 5-7

Stage Graph at Dam

(Rain Interval 1; High Base Flow)



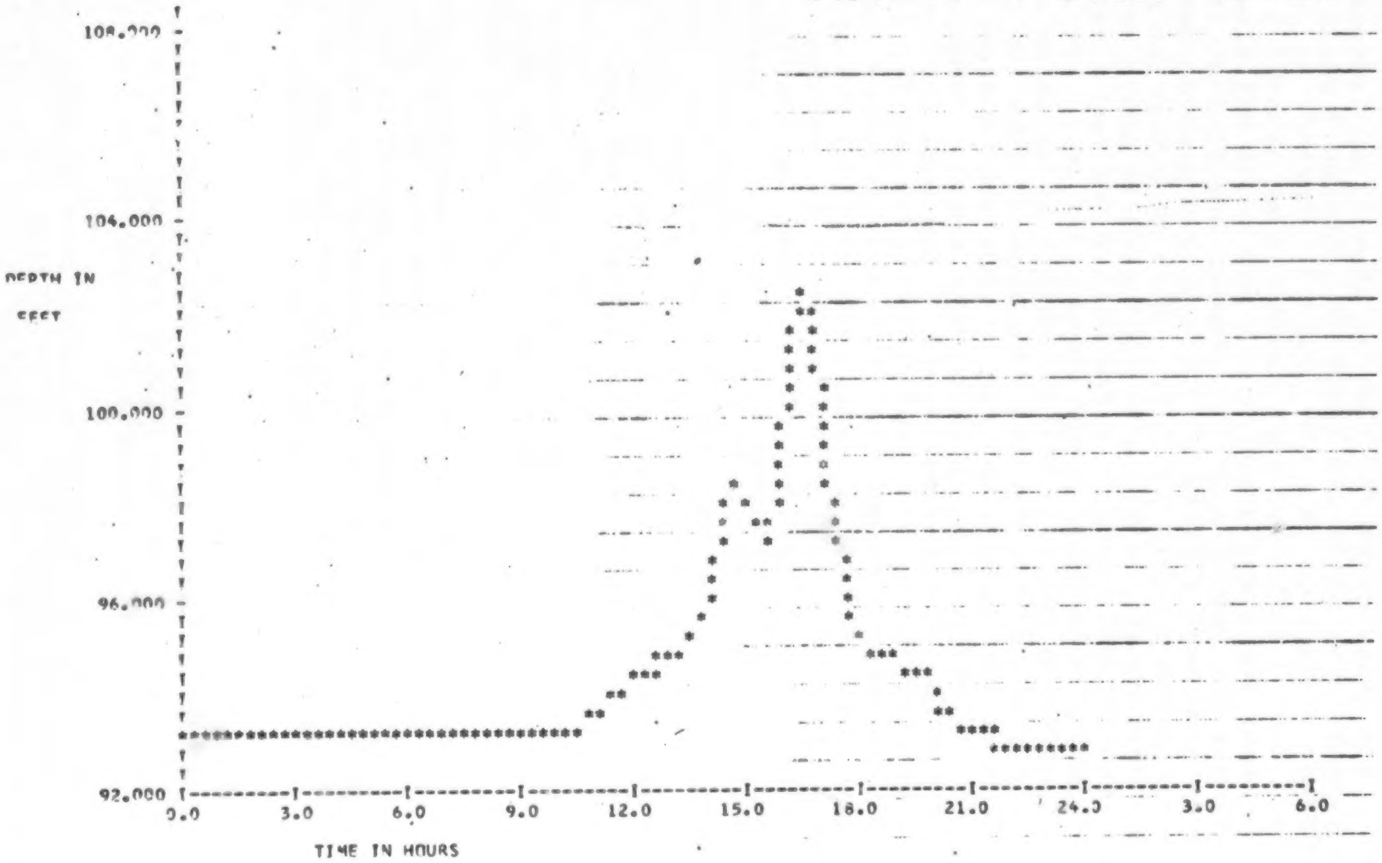
A. Land Use 1974

B. Land Use 1985

Figure 5-8

Stage Graph at Junction 8

(Rain Interval 1; High Base Flow; Land Use 1974)



8). The stage graph for the dam shows lump effects from all upstream input while the graph at junction 8 still reveals characteristics of the hydrograph at junction 8: a first peak after 3 p.m., and then another peak after 5 p.m. The fact that the stage graph at the dam tails off slowly reflects the upstream inflow, though due to fast travel times some peak effects of the upstream portion get absorbed in the peaks of this junction. Here we encounter problems with rectangular channels as indicated in above sections. An intermittent river like the Mill River has a very small bed, but a relatively large flood plain area. It is possible to compensate for this characteristic by assuming a relatively wide profile for the base flow so that the dampening effect of the flood plain can be accounted for during higher flows. However, such an assumption creates numerical problems because of the shallowness of the base flow through a wide river bed. If a small profile is set for base flow according to the actual bed size, the increased flow during a rain input greatly increases the velocity and produces an unrealistic water stage level; Figure 5-8 documents this problem. The analyst has to find some compromise, such as using storage nodes or parallel channels, to absorb some of the flood plain effects.* Another problem occurred when a stage graph at the dam (for the same high base flow and runoff from rain interval 1) revealed a very rapidly rising and falling crest. This had been caused by rapid travel times in the river. The rapid travel times were induced by low values of the Manning coefficient. Since no travel time analysis had been done for the Mill River, Manning coefficients close to the default values in SWMM were used in the first runs, and resulted in unrealistic travel times.**

Table 5-14 shows the behavior of suspended solids and Table 5-15 the behavior of coliforms for rain interval 1 (land use 1974) where the first rain period is from 10 a.m. to 6 p.m. with 1.63 inches of precipitation and the second period of precipitation is during the next day (9 a.m. to 4 p.m.) with an accumulation of only .56 inches. Due to

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* Budget and time did not permit an exploration of these options. But we feel that these problems frequently encountered have not been adequately documented in the literature.

** For example, Whipple's description of selecting the right Manning coefficient also reflects how inadequate, simple assumptions such as default values of .018 (as given in SWMM's manual) can lead to unrealistic results ("BOD Mass Balance and Water Quality Standards," Water Resources Research, Vol. 6, No. 3, June, 1970).

Table 5-14

Suspended Solids (mg/ℓ) - Rain Interval 1 - High Base Flow

Land Use 1974

Time \ Junction	1	2	3	4	5	6	7	8	9	10	11	12	13
8	11.8	13.	8.9	8.6	8.6	9.1	9.1	9.1	9.2	9.2	8.5	8.9	7.9
10	11.7	16.9	8.9	8.9	11.2	11.6	10.1	11.3	10.2	9.4	10.5	13.3	21.5
12	11.6	22.3	9.3	13.2	13.2	13.7	12.3	11.	10.8	14.	12.	10.	8.3
14	11.4	[illegible].2	11.1	17.3	27.5	27.5	17.1	24.7	15.5	9.7	15.9	24.7	19.4
16	11.7	102.9	21.	27.7	31.5	39.6	20.4	26.2	17.5	12.9	14.7	27.1	19.4
18	15.4	26.3	29.	28.9	15.9	23.1	11.6	10.	8.5	10.5	10.1	5.7	3.4
20	17.9	24.6	24.7	21.4	11.4	10.3	8.	10.	9.5	6.4	5.7	8.9	11.3
22	18.5	24.6	22.1	10.	8.7	9.5	9.4	6.9	7.4	9.9	7.5	8.9	10.2
24	18.6	24.6	19.4	8.9	8.9	8.1	7.7	9.7	8.6	9.7	7.8	8.9	9.6
4	18.6	24.6	17.4	8.0	7.7	8.8	8.8	9.5	8.8	9.6	8.0	8.9	9.2
8	18.2	24.6	13.2	8.6	8.6	9.2	8.9	9.3	9.0	9.3	8.3	8.9	8.4
10	18.0	22.6	[illegible].4	8.6	8.4	9.	8.8	8.9	8.8	8.6	7.3	7.7	6.1
12	17.7	18.2	11.6	8.0	7.8	8.3	8.1	8.	7.4	6.9	5.3	6.6	4.7
14	17.1	14.9	10.4	7.7	7.4	7.6	7.	6.7	6.1	6.2	5.2	6.5	4.6
16	16.5	12.3	9.3	7.1	6.6	6.4	6.1	6.1	6.	6.1	5.	6.4	4.4
18	15.9	11.5	8.4	6.2	6.	6.	6.1	6.5	6.2	6.9	5.7	8.9	11.2
24	14.6	11.5	7.2	6.8	7.2	8.7	8.8	9.5	8.7	9.6	8.0	8.9	9.2

Runoff occurred from 10:00 to 18:00 hours and on the next day from 9:00 to 16:00 hours.

Table 5-15

Coliform (10^3 MPN/100 ml) - Rain Interval 1 - High Base Flow

Land Use 1974

Junction / Time	1	2	3	4	5	6	7	8	9	10	11	12	13
8	.06	.08	.007	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
10	.06	27.0	.6	1.6	15.0	16.0	4.8	12.0	5.5	1.5	11.0	25.0	76.0
12	.07	57.0	2.6	25.0	24.0	24.0	16.0	9.7	10.0	30.0	22.0	11.0	12.0
14	.4	70.0	11.0	26.0	26.0	22.0	14.0	27.0	16.0	8.6	11.0	11.0	8.6
16	2.6	16.0	22.0	16.0	10.0	21.0	11.0	5.9	6.4	4.1	1.6	1.6	1.1
18	7.5	4.2	12.0	15.0	8.2	5.1	4.0	2.8	0.75	0.5	.57	.05	.05
20	8.5	3.9	12.0	4.7	3.6	3.0	0.6	.37	.36	.03	.001	.001	.001
22	8.7	3.9	9.4	2.7	1.4	.72	.3	.022	.001	.001	.001	.001	.001
24	8.7	3.9	7.8	.74	.44	.21	.01	.001	.001	.001	.001	.001	.001
4	8.7	3.9	6.5	.22	.1	.13	.001	.001	.001	.001	.001	.001	.001
8	8.3	3.9	3.5	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
10	8.1	6.1	2.9	6.1	1.4	1.3	.66	.85	.35	.28	1.7	1.3	1.4
12	7.8	6.8	2.5	1.7	1.6	1.5	.8	.7	.12	.97	1.0	.67	.67
14	7.3	6.3	2.3	1.5	1.2	.98	1.2	.97	.71	.50	.58	.39	.39
16	6.8	5.5	1.9	.98	1.2	1.1	.69	.51	.41	.29	.33	.23	.22
18	6.4	5.1	1.6	.95	.65	.54	.32	.23	.22	.13	.001	.001	.001
24	5.7	5.1	.99	.14	.07	.03	.001	.001	.001	.001	.001	.001	.001

Runoff occurred from 10:00 to 18:00 hours and on the next day from 9:00 to 16:00 hours.

the high base flow associated with relatively low suspended solids concentration (which might be a doubtful assumption) the suspended solid concentration in the river due to runoff remains quite insignificant, except for the one peak inflow from the most urbanized area of the basin, the western part of Lake Whitney (junction 2). Generally, the concentrations ranged from 40 mg/ℓ to figures as low as 3.4 mg/ℓ at the end of the runoff period when runoff contains almost no washoff. The second rain period does not contribute to an increase in concentration except at junction 2. Small storms following a large storm do not have much material to wash off in impervious areas. For instance, in this case, figures for Shepard Brook indicate that in the first ten hours, 51,800 pounds of dust and dirt were washed off from the subbasin by 1.56 inches of rain, while during the second event only 1,599 pounds were washed off by .56 inches of rain. It should be noted that combined input of erosion generated by the universal soil loss equation and washoff from the urbanized areas would have significantly increased the concentration figures of suspended solids. But intensive testing of a combination of these two options has not been done. The accumulation of suspended solids and then the slow drop-off of the concentration in the downstream portion of the lake can be easily recognized. The time of delay from the peak flow at around 4:00 p.m. to the peak concentration is approximately ten hours. The trend of coliform is similar to that of suspended solids. A similar delay of the peak concentration can be found; contribution of the second storm is minor except at junction 2; and concentrations are generally not very high.

The second rain interval (June 16, 7 p.m. to 9 p.m., precipitation of .51 inches after a dry antecedent period of 367 hours) has been investigated for two flow conditions: one accumulates to 105 cfs at the dam (called medium flow) and the other to 69 cfs (called low flow). Figure 5-9a, the stage graph at the dam for low flow condition and 1974 land use, reveals two peaks: one caused by the nearby heavy runoff and the second by accumulated upstream effects. In contrast to this graph, the stage graph of the first rain interval (Figure 5-7a), which started from a much higher stage due to the high base flow, did not reveal these peaks because the ten hour interval of rain at that specific intensity distribution dampened the upstream peak effects. The figures show that the peak caused by rain interval 2 is smaller than that of interval 1 by approximately .65 feet stage level. The stage graph based on the medium flow condition has the same shape but the falling crest is contracted by approximately two hours due to the shorter travel times.

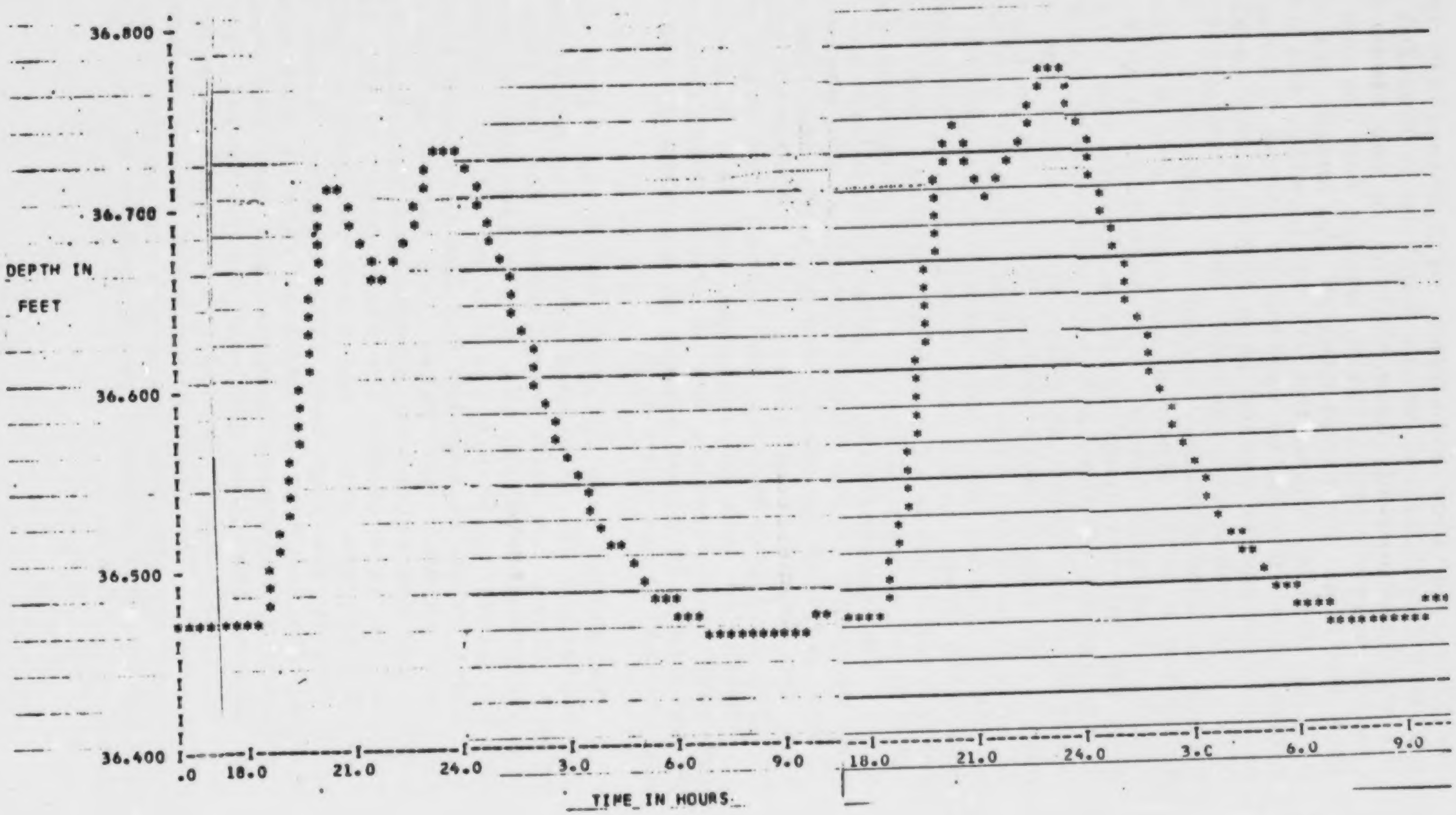

Figure 5-9

Stage Graph at Dam

(Rain Interval 2; Low Base Flow)

A. Land Use 1974

B. Land Use 1985

Table 5-16a* presents the behavior of the coliforms during interval 2 for low flow and the 1974 land use conditions. Relatively high concentrations prevail compared to the coliform concentration in the river system during the first rain interval. The final concentration at the dam (junction 1), however, is in the same order of magnitude. Due to the reduced base flow, the time of delay between peak flow and highest concentration increases to at least one day. The slow movement of the coliform concentration down the river can be easily recognized. The coliform concentrations for the medium base flow conditions during the same rainfall are different from the concentration under low flow conditions only in so far that they are approximately 1-1/2 times lower than the concentration during low flow. That is consistent with the same input of constant as well as time dependent coliform load at all the junctions, while the flow for the medium condition is approximately 1-1/2 times as high as for the low flow. The travel times in the low flow case are a little slower and therefore slightly change the path configuration of the coliform concentration in the system. Clearly, a much higher flow and a longer period of precipitation during interval 1 induces a very different coliform distribution in the river system. But again, the final concentration at the dam is in the same order of magnitude, which is consistent with the fact that the total input of coliform is in the same order of magnitude for both amounts of runoff. The trend of suspended solids (Tables 5-15 and 17a) during intervals 1 and 2 is similar to the trend of coliforms during those intervals; there are much higher concentrations in the system during the immediate time of precipitation in interval 2 and for some time afterwards, but final concentrations at the dam are in the same order of magnitude; again the rate of increase to the peak concentration at the dam is much slower in the second interval due to reduced travel times.

After we compared the impact of the 1974 land use configuration on the water body during different rain intervals, we turned to the comparison of the impacts due to different land use patterns. The first condition we considered was the intensive development in Shepard Brook as described in Appendix B, Table B-6. The intensive development is characterized by addition of residential, commercial and industrial subdivisions to the 1974 development of the sub-basing. For rain interval 1, the peak of the stage graph at the dam (Fig. 5-10) is slightly higher

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* In order to make possible comparisons between 1974 and 1985 land uses, not all of the junctions are presented.

Table 5-16

Coliforms (10^3 MPN/100 ml at Junctions of Mill River System
Rain Interval 2 - Low Base Flow

A. Land Use 1974

B. Land Use 1985

Junction / Time	1	3	6	8	11	12	1	3	6	8	11	12
18	.08	.03	.002	.002	.002	.003	.08	.03	.002	.002	.002	.003
19	.08	.03	68.0	59.0	47.0	350.0	.08	.03	94.0	86.0	81.0	180.0
20	.08	9.2	92.0	55.0	210.0	49.0	.07	8.7	130.0	120.0	180.0	49.0
21	.36	25.0	62.0	17.0	34.0	49.0	.37	32.0	99.0	69.0	33.0	49.0
22	1.0	34.0	53.0	30.0	2.6	49.0	1.4	47.0	100.0	57.0	2.6	49.0
23	2.0	39.0	25.0	110.0	7.7	.003	3.0	56.0	76.0	89.0	7.1	.003
24	3.3	43.0	27.0	18.0	2.6	.003	5.1	63.0	66.0	18.0	2.3	.003
2	5.4	42.0	49.0	3.8	.21	.003	8.5	70.0	62.0	3.6	.2	.003
6	7.0	41.0	17.0	.8	.004	.003	10.0	69.0	38.0	.78	.02	.003
14	8.8	32.0	1.7	.002	.002	.003	14.0	53.0	.33	.002	.002	.002
24	9.8	25.0	.002	.002	.002	.003	16.0	41.0	.01	.002	.002	.003

Runoff occurred from 19:00 - 21:00 hours.

Table 5-17

Suspended Solids (mg/ℓ) Rain Interval 2 - Low Base Flow at Junctions of Mill River System

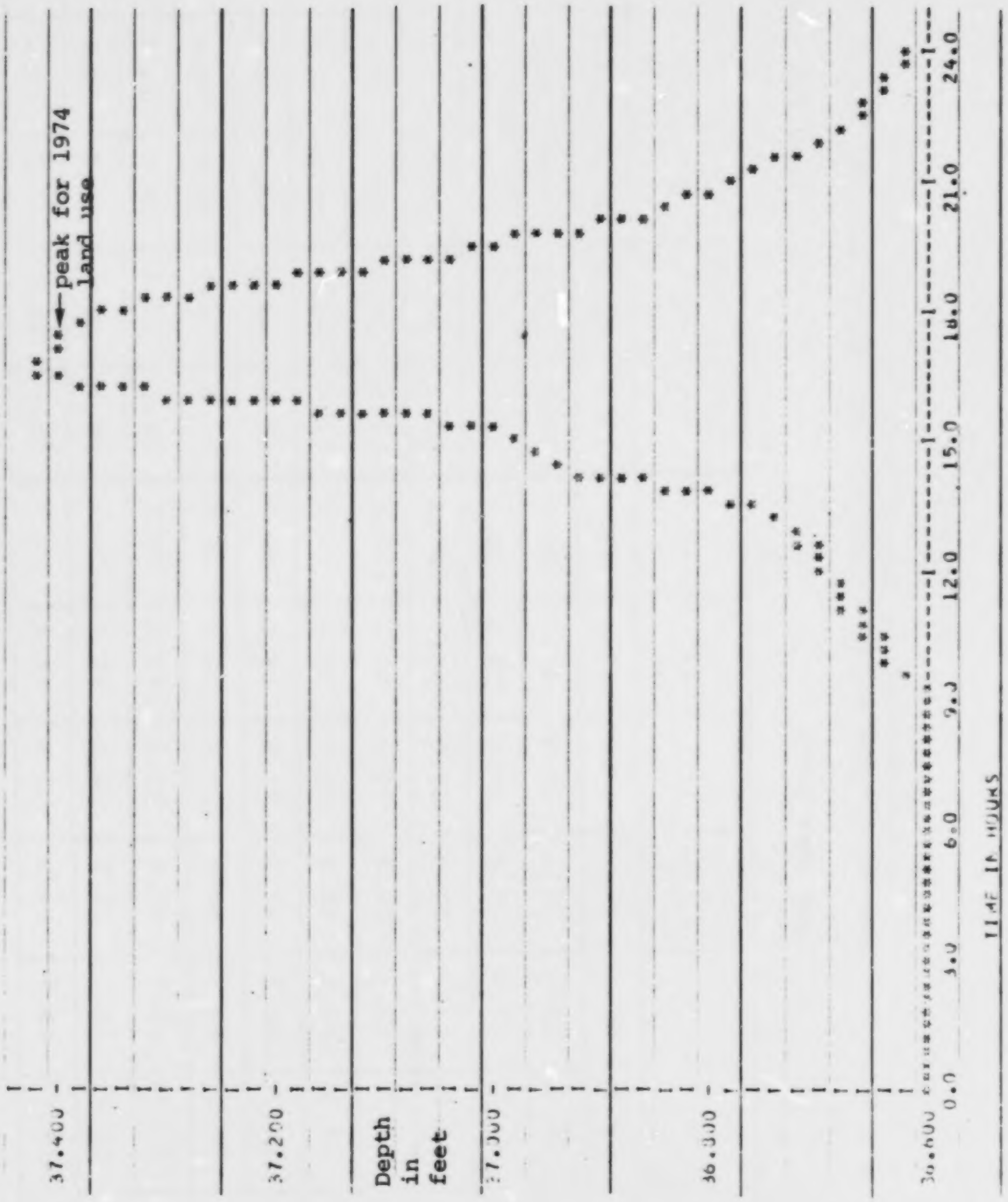
	A. Land Use 1974						B. Land Use 1985					
Junction / Time	1	3	6	8	11	12	1	3	6	8	11	12
18	13.0	13.1	14.2	14.2	15.4	25.7	13.0	13.1	14.2	14.2	15.4	25.7
19	13.0	13.1	33.3	37.2	41.3	190.7	13.0	13.1	37.8	42.7	48.6	109.4
20	13.0	15.6	77.8	75.8	158.5	125.6	13.0	15.5	90.5	88.2	139.9	125.6
21	13.1	23.1	59.0	37.5	88.9	125.6	13.1	24.9	70.5	55.0	83.4	125.6
22	13.3	32.7	66.9	50.9	10.8	125.6	13.5	38.5	78.1	58.5	9.1	125.6
23	13.9	36.5	44.0	87.1	23.9	27.7	14.4	43.5	59.8	71.6	21.6	25.7
24	14.7	40.0	47.2	51.8	18.4	25.7	15.5	48.3	58.7	50.5	17.7	25.7
2	16.1	43.7	60.1	17.4	16.0	25.7	17.5	53.1	60.6	16.3	15.9	25.7
6	17.35	44.7	30.8	13.9	15.1	25.7	18.4	53.6	44.1	14.4	15.2	25.7
14	18.6	40.5	14.7	14.2	15.3	25.7	20.9	45.3	14.4	14.1	15.4	25.7
24	19.7	33.1	14.2	14.2	15.3	25.7	21.9	38.1	14.2	14.2	15.4	25.7

Runoff occurred from 19:00 - 21:00 hours.

Figure 5-10

Stage Graph at Dam

Rain Interval 1; High Flow; Intensive Development in Shepard Brook



than in the 1974 configuration, while the shape is identical. The concentration of coliforms and of suspended solids for this scenario are slightly increased compared to the 1974 land use, but the increase is in a range which is not of appreciable significance for the public health official or the concerned public. Due to the minor changes, the comparison of the land use scenarios was limited to the rain interval 1.

The next land use scenario we investigated is based on the land use plan of 1985 for Hamden. Using this plan, we have specified input parameters to the STORM model as accurately as possible given the quality of information. Population increase over today's figures is estimated at approximately 13,000, distributed in the upper part of the basin. The population in the area of Lake Whitney was kept constant. Commercial and industrial areas were added as far as they could be recognized from the 1985 land use map. Figure 5-7b shows the stage graph of rain interval 1 at the dam. Its shape is clearly comparable to the base case (Figure 5-7a), but the peak is increased by approximately .1 foot of water level. Increased travel times due to the higher flow from the increased runoff causes a slight contraction of the graph as can be seen, for instance, at the 37.0 feet mark. Comparing the stage graphs of rain interval 2 for the low flow case yields similar results (Figure 5-9b). The stage graph shows the same shape but both peaks are slightly higher, in a range of .15 feet. Again the falling crest of the 1985 scenario is a little bit steeper than that of the 1974 graph. Table 5-18 shows the suspended solids concentration, and Table 5-19 the coliform concentration for the 1985 land use scenario during rainfall interval 1. The base flow conditions were kept the same as above. Significant differences can be extracted by comparing the Tables 5-14 and 5-15 (reflecting the 1974 land use condition) with the Tables of the 1985 land use plan. The 1985 concentrations in the system are approximately 1-1/2 times as high for the coliform, while only approximately 30 percent higher for the suspended solids. The peak of concentration is approximately at the same time, about 4 to 6 p.m., which is eight to ten hours after the rain has finished. Similar observations can be made for rain interval 2 as indicated by comparison of Tables 5-16a and b and 5-17a and b for coliform and suspended solids concentration, respectively. The peak concentration of suspended solids at the dam increases only slightly for the 1985 development pattern, from 19.7 to 21.9 mgℓ, while the highest coliform cōncentration increases from 9,800 to 16,000 MPN/100 mg/ℓ. The peak concentration itself does not seem as important as the trend revealed. Yet, even though the concentration increase is not relevant in terms of public health considerations for the Mill River,

Table 5-18

Suspended Solids (mg/ℓ) - Rain Interval 1 - High Flow

Land Use 1985

Junction / Time	1	2	3	4	5	6	7	8	9	10	11	12	13
8	11.8	13.0	8.9	8.6	8.6	9.1	9.1	9.1	9.2	9.2	8.5	8.9	7.9
10	11.7	16.9	8.9	8.9	12.5	12.3	11.2	12.2	12.2	11.1	12.1	13.3	27.4
12	11.6	22.3	9.5	15.0	15.2	15.7	14.9	14.0	14.2	16.7	13.7	9.9	9.7
14	11.4	63.1	11.8	19.9	35.9	33.9	25.9	31.7	27.2	19.5	22.0	24.7	26.3
16	11.9	102.5	25.2	32.5	44.2	48.5	35.0	37.2	33.3	25.4	23.4	27.0	26.5
18	17.3	26.8	39.0	34.6	26.4	31.5	20.2	17.1	10.4	8.9	9.7	5.7	3.4
20	21.4	25.1	33.2	29.0	19.0	17.3	9.5	8.7	9.0	6.3	5.6	8.9	11.3
22	22.3	25.1	30.2	16.3	11.9	9.8	8.9	6.9	7.4	9.9	7.5	8.9	10.2
24	22.6	25.1	26.8	9.7	8.9	8.0	7.6	9.7	8.6	9.7	7.8	8.9	9.6
4	22.8	25.1	20.5	8.2	8.3	9.2	8.9	9.4	8.9	9.5	8.1	8.9	8.8
8	22.5	25.1	16.4	8.6	8.6	9.2	9.0	9.3	9.0	9.3	8.3	8.9	8.4

Runoff occurred from 10:00 to 18:00 hours.

Table 5-19

Coliform (10^3 MPN/100 ml) - Rain Interval 1 - High Flow

Land Use 1985

Junction / Time	1	2	3	4	5	6	7	8	9	10	11	12	13
8	.06	.08	.007	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
10	.06	27.0	.006	1.6	23.0	22.0	13.0	18.0	22.0	11.0	20.0	25.0	110.0
12	.07	57.0	3.6	35.0	36.0	37.0	34.0	28.0	28.0	43.0	28.0	11.0	17.0
14	.58	70.0	15.0	39.0	41.0	41.0	32.0	41.0	30.0	16.0	16.0	11.0	12.0
16	4.0	17.0	32.0	23.0	29.0	30.0	19.0	10.0	9.4	5.1	2.3	1.6	1.6
18	12.0	4.3	22.0	21.0	14.0	8.5	5.5	3.2	.89	.39	.56	.05	.07
20	14.0	4.1	19.0	7.7	5.0	3.6	.7	.32	.35	.03	.03	.05	.001
22	14.0	4.1	15.0	3.3	1.6	.78	.29	.03	.001	.001	.001	.001	.001
24	14.0	4.1	12.0	.83	.47	.22	.01	.001	.001	.001	.001	.001	.001
4	14.0	4.1	8.2	.4	.02	.01	.001	.001	.001	.001	.001	.001	.001
8	13.0	4.1	5.4	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001

Runoff occurs from 10:00 to 18:00 hours.

an increase of this size might be relevant in another river basin and result in potential danger to the public health.

These runs have demonstrated that, given similar base conditions in a river system, the impact of different development scenarios can be identified. Existing qualitative knowledge can be quantified with this combination of models.

How useful are the results of these runs? Results of STORM, reported in Appendix B, seem to be in the same order of magnitude as results reported in the literature. SWMM has been tested by its developers and its performance has been found satisfactory. Clearly, significant problems of calibration and verification occur when such a chain of models is to run for many different situations. Are our results useful despite the lack of detailed calibration? The concentration figures computed by SWMM at the dam site seem to be in the right order of magnitude and to reveal the right tendency, if we assume that it is possible to compare SWMM's hourly results to daily samples from the New Haven Water Company. The samples of the water company show that during periods of heavy precipitation the samples of coliform are in the range of the results generated by SWMM. It is impossible to be more specific in the interpretation because we do not know at what time of the day the samples were taken and to what degree the distribution of precipitation in Hamden is reflected in the precipitation record of Bridgeport airport. Cross-series analysis of the Water Company's coliform and water-stage records (monitored at the dam) yield a peak of the cross-variance for a time lag of one day and a peak of roughly .55 days in the cross-spectrum analysis.* The small discrepancy is caused by the different degree of discretization in the cross-series analysis package. But clearly, a lag effect is existent; and these lag effects are also indicated in our simulation of runoff and washoff. During interval 1 the peak of coliform concentration lags behind the peak of the water stage by about 1/2 day. The concentration decreases then quite slowly over the period of 12 to 24 hours after the stage peak. During the rain interval 2 the lag increased to at least one day, confirming the above results. Disagreement between calculations and sampling could arise because samples are taken in the middle of the rain interval when the stage is already high but the coliforms still low.

In summary, the linkage of STORM and SWMM is of great value to our land use water quality analysis (Table 5-20 summarizes the steps of the analysis). Results permit identification of the impact of different land use patterns on the magnitude of pollution from urban storm water runoff. In the case of the Mill River it revealed that a quite large increase of pollutant emissions has to be expected within ten years. When standards are violated, the costs of alternative methods of control and their impact have to be evaluated (see section 6).

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* That means that this frequency contains the most common variance of the two series.

Summary

The computer models developed in this section provide local and regional planners with a flexible tool for evaluating the effects of land use patterns on the utilization of wastewater-related infrastructure (see the sewer and treatment plant capacity evaluation module), the magnitude of waterborne emissions from urban runoff, and the resulting water quality of receiving streams in response to runoff, washoff, and erosion. The models can be employed to analyze both the impacts of individual developments and of zoning policies applied to an entire sub-basin. In addition, the impacts of alternative land uses and emission controls can be assessed with this module.

In our introduction to this report, we stressed the necessity of considering the interaction between environmental, social, and economic impacts in the land use planning process. Within this framework, the environmental impact and capacity evaluation models such as the ones developed here perform several important functions:

1. 208-areawide planning calls for an evaluation of the environmental impact of alternative physical and land use controls for water quality management. Areal sources as well as discharges from treatment plants have to be considered. Previously, facility planning under Section 201 of Public Law 92-500 had been concerned primarily with treatment plants and major interceptors. Their utilization rate can be estimated by the capacity evaluation module. Demonstration runs with the model combination of STORM-SWMM have shown its applicability for investigating land use control alternatives and pollution from urban runoff. Discrimination between quality impacts from different land use configurations is possible. Thus the model enables planners to consider and compare relevant controls.

2. Local land use decision-making takes place in a context where certain groups show strong concern for the environmental impact and for the potential overutilization of infrastructure. By making it possible to predict this

Table 5-20
Summary of Analysis

Steps	Wet Flow
Level of Aggregation	Define receiving waterbodies and sub-basins (idealize in junctions and channels).
Land Use Analysis for Specified Year	Define number of land use catories per sub-basin and land use controls.
Land Use Parameter Estimate per Land Use Cagegory (urban; non-urban)	Rate of imperviousness; runoff coefficients; rate of dust and dirt accumulation; select pollutants of interest; dust and dirt breakdown into pollutants; pollutant emission (specify seasonal or yearly average parameter).
Generation of Input to Waterbody (subject to storage specifications)	Select rain invervals of interest; run STORM on all sub-basins for the specified simulation period; calculate total runoff and total load for simulation period; compute load and runoff of specified intervals; save on disk.
Calibration of STORM	In case of runoff **gauging** and washoff monitoring, calibrate (and verify) quantity and quality modules.
Universal Soil Loss Function	Use for erosion and sediment load, if desired.
Estimating Receiving Waterbody Parameter Parameters	Hydraulic, hydrologic and quality related parameters in SWMM; select integration step.
Calibration/**Verification Exercise**	Use steady-state flow; point source input (see calibration exercise as described), if specifically distributed data are available.
Route Quantity and Quality in Waterbody	Select runoff event(s) of interest; select pollutants; select background hydrograph and pollutograph; route; print stagetime relationship and pollutant change at specified junction.
Adjust Calibration	In case of available high-flow data adjust quality related parameters; multiple runs of quality module.
Rerun and Analyze	Make all desired runs; compare results; evaluate frequencies of water quality conditions of interest.

impact to a certain extent, these models will serve to facilitate local decisionmaking.

3. By indicating the impact of areawide as well as local development given for existing pollution control standards, the model will enable planners to determine if these impacts are undesirable by existing standards. Policies can then be designed to alleviate any undesirable impacts which may be revealed.

4. The output of the capacity evaluation module can be used as input to the fiscal input model.

5. The models developed in this section presently consider only a restricted set of land uses and land characteristics, and employ functions which may need considerable refinement and re-evaluation. Nevertheless, we feel that the models, if used properly within their limitations will give results which are valuable for many planning purposes.

Section 6

Land Use/Water Quality: Fiscal Impact

Introduction

Our concern in this section is the direct fiscal impact of pollution control and, in particular, of water pollution control. These impacts include the costs of waste transport and treatment, the additional costs of employing alternative activities or processes, and the manner in which these costs are allocated to different governmental levels and socio-economic classes. We are not concerned here with indirect economic impacts, either positive or negative, resulting from pollution control activities, such as the creation of jobs to build treatment plants or the loss of jobs resulting from closing an antiquated, polluting plant. These, of course, can be significant in some instances. Nor are we concerned with economic measures of the damage (or benefit) resulting from various ambient pollutant concentrations, although there has been considerable interest in obtaining such measures, particularly for air pollutants.*

Our discussion here follows the patterns set in our treatment of generation and emission models in that we separate the analysis into two categories: wastewater and stormwater controls. This approach also follows the conventional engineering practice of separating sanitary sewerage from stormwater. This practice may change in the future because it is becoming increasingly evident that control of stormwater will be required to meet water quality goals. An attractive alternative to accomplish this is to revert to combined wastewater and stormwater treatment. However, other options also are available and as yet no definite commitment to any of these alternatives has been made on a national scale. Thus in our review here we do not discuss combined sewerage systems or stormwater treatment cost (other than for simple storage for sediment and runoff control).

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* See for example, T. Waddell, "The Economic Damages of Air Pollution," Environmental Protection Agency, EPA-600/S-74-012, 1974; also D. P. Tihansky, "Economic Damages to Household Items from Water Supply USe," Environmental Protection Agency, EPA-600/S-73-001, 1973.

A Brief Review of Existing Models

There are three basic models or modeling approaches which are covered in this section:

1. wastewater treatment;
2. collection and transport of wastewater at the development and interceptor level; and
3. collection and transport of stormwater at the development and interceptor level.

Models for Wastewater Treatment Costs

A substantial literature exists on the estimation of capital and operating and maintenance costs for wastewater treatment plants. We therefore will cover this topic only briefly here. Smith* has reviewed and summarized much of the early literature in this field. Subsequent work for the EPA** has further extended the literature on treatment plant costs and updated cost estimates to account for the requirements of the 1972 Amendments to the Water Pollution Control Act and to EPA's interpretations of these amendments. Techniques employed in these studies have included costing of hypothetical treatment plant designs as well as empirical analysis of actual plants built under various federal and local programs.

Traditionally, the costs of wastewater treatment have been modeled as simple power functions of a single variable, usually total flow, population equivalents served, or BOD load. This formulation is deficient in two major respects. First, costs are affected both by hydraulic and organic loadings and thus a cost estimating procedure based upon only one of these variables may be misleading. Shah and Reid*** have devised cost estimating equations from a regression analysis of a sample of actual treatment plant projects. Cost was modeled as a power function of both organic loading and total flow. Both variables were found to be significant in the regression.

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* R. Smith, "Cost of Conventional and Advanced Treatment of Wastewater," J. Water Pollution Control Federation, V. 40, September, 1968, pp. 1546-74.

** For example, Black and Veatch Consulting Engineers, "Estimating Cost and Manpower Requirements for Conventional Wastewater Treatment Facilities," Environmental Protection Agency, 1971.

*** D. L. Shah and W. Reid, "Techniques for Estimating Construction Costs of Waste Treatment Plants," J. Water Pollution Control Federation, V. 42, May 1970, pp. 776-93.

A second drawback of the conventional formulation is that it implies a constant elasticity of cost with respect to plant size over all capacities. Most of the data which have been accumulated are for relatively small plants (1-10 mgd) which exhibit significant economies of scale. Thus extrapolation of these economies to larger size plants might be inappropriate and could lead to excessively large regional plants and over-expansion of facilities. In fact, more recent evidence* indicates that the economies of scale in larger plants are not as great as in the smaller facilities.

Another aspect is advanced wastewater treatment, associated with higher treatment requirements. The costs of two treatment plants should be compared only when the same treatment levels are required. Technology significantly influences the total capital and operating costs. For example, certain cheap treatment technologies such as lagoons are available only for small plants, not for large plants.**

Modeling Collection Costs

While a considerable amount of effort has been spent on obtaining accurate generalized cost estimation procedures for wastewater treatment processes, much less attention has been given to developing suitable cost estimation procedures for wastewater collection. This relative neglect is somewhat surprising in light of the fact that collection costs account for 50 to 70 percent of the capital costs of a wastewater disposal system.

In a model of wastewater collection costs for both new development areas and the accompanying interceptor systems, there are a considerable number of factors which must be taken into account since they markedly affect costs. To set the background for our discussion, these factors are discussed briefly below under the categories of engineering standards and natural factors.

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* R. Smith and R. G. Eilers, "The Economics of Consolidating Sewage Treatment Plants by Means of Intercepting Sewers and Force Mains," Environmental Protection Agency, 1971.

** "An Identification of the Municipal Choice of Options for Meeting the Effluent Limitations and Goals Specified in Public Law 92-500," in preparation by Meta Systems Inc for the National Commission on Water Quality, Contract No. WQ5AC047, 1975.

As in any engineering project, the costs of a sanitary sewer system are heavily influenced by prevalent engineering design standards. Such standards include factors of safety and implicitly reflect the best judgments of the profession regarding the tradeoffs between initial capital, operating and maintenance, and replacement costs and between cost and reliability or other measures of performance. Fortunately, from the standpoint of devising generally applicable cost estimates, there appears to be widespread agreement on many of the important standards for sanitary sewer design.* Indeed, the design of sanitary sewer systems has become so standardized that Newville was moved to comment:

> The basic parameters for sanitary sewer design were set at the turn of the century and, for the most part have remained unquestioned since that time. Sewerage collection systems today are designed almost by rote, picking values off charts and conforming to standards which were in existence before the present generation of engineers were born.**

Although many aspects of sanitary sewer design are well established, in practice some design standards are subject to state and local variation. These standards include minimum pipe size, infiltration allowance, per capita flow, ratio of peak to average flow, and minimal depth of placement.***

Besides engineering standards, several natural factors also have a bearing on sewer designs. They are as follows:

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* This does not imply that these standards are necessarily rational or that they are not likely to change in the future, however.

** Jack Newville, New Engineering Concepts in Community Development, Urban Land Institute Technical Bulletin 59, Washington, D. C., 1967.

*** For a complete discussion of how these standards influence costs, see "Data Collection and Review and Analysis of Infrastructure Cost Relationships," Working Paper No. 3, prepared for the Environmental Protection Agency by Meta Systems Inc under Contract No. 68-01-2622, February 15, 1975.

1. Soil Type. The soil type determines the ease of excavation and therefore is a major factor in determining costs. For example, according to the Dodge Guide,* the unit cost of excavation in clay is about 1.7 times that of common earth, and rock excavation costs are five times that of common earth. In areas with extensive bedrock near the surface, it may be infeasible to install traditional sewerage systems at typical suburban densities.

2. Depth to Water Table. A high water table increases excavation and installation costs by adding requirements for dewatering and sheeting of the excavation. A variety of methods are available for this purpose, and the selection of a particular technique depends upon the severity of the problem. In extreme cases, the additional costs can be as great as those imposed by the excavation of rock.** The depth to water table also can affect the infiltration allowances employed in sewer design.

3. Topography. Because of the high cost associated with trenching, particularly the sheeting and bracing cost, the most economical sewer system designs are generally those which minimize the total amount of excavation. Thus the most economical design would be obtained where all collectors could be placed at minimum depth, that is, parallel to the surface slope. Unfortunately, there are upper and lower limits on the slope conditions under which these ideal conditions could be met. These limitations are derived from the minimum and maximum velocity requirements which have been adopted as part of engineering design practice.

Development Level Costs. Taking into consideration these factors, we have reviewed a number of studies of wastewater collection costs at the development level, and summarize below their approaches and major results. The studies reviewed were conducted by the Urban Land Institute

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* 1975 Dodge Guide for Estimating Public Works Construction Costs, New York: McGraw Hill, 1974.

** R. S. Howe, "Planning Sewerage Service for New Towns," Ph.D. Thesis, University of Wisconsin, 1971.

(ULI),* Downing,** Dajani and Gemmell (DG),*** the Real Estate Research Corporation (RERC),† and Howe.†† A detailed comparison of the design methodologies employed in these studies is presented in Table 6-1.†††

All these studies represent synthetic costing efforts. That is, the authors laid out what they felt were representative land use patterns and assembled the costs for sewering these patterns from the unit costs of pipes, excavation, and appurtenances.

All of the studies began with a basic geographic unit of analysis. In the case of the ULI study, the basic unit was a 1000-acre community. Downing, DG, and Howe employed a 160-acre (1/4 square mile) subdivision as their basic unit while RERC defined a basic unit in terms of a constant number of dwelling units (1000). Each study then proceeded to design and estimate sewer system costs for different densities and housing types on their basic unit. Here, however, the paths of the studies diverged. The ULI and RERC studies paid a great deal of attention to the layout of the system. The RERC study assumed modern curvilinear

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* Urban Land Institute, "The Effects of Large Lot Size on Residential Development," Technical Bulletin 32, Washington, D.C., 1958.

** P. B. Downing, The Economics of Urban Sewage Disposal, New York: Praeger, 1969.

*** J. S. Dajani and R. S. Gemmell, "Economics of Wastewater Collection Networks," University of Illinois Water Resources Center, Research Report No. 43, June, 1971.

† Real Estate Research Corporation, The Costs of Sprawl: Detailed Cost Analysis, prepared for the Council on Environmental Quality, Department of Housing and Urban Development, and the Environmental Protection Agency, Washington, D.C., U.S. Government Printing Office, April, 1974.

†† R. S. Howe, op. cit.

††† For purposes of comparison we have already introduced our approach in this table, even though it is not described until Section 6, page 16.

Table 6-1

Summary of Sewerage Studies

		Urban Land Institute	Downing	Dajani and Gemmell	Howe	RERC	Meta
Network Characteristics	Basic Unit Size	1000 acres	160 acres	160 acres	160 acres	1000 dwelling units	160-200 acres
	Gross Densities (PPA)	3.4,6.5,12.2	0.4,1,4,16,64, 128,256,512	10,25,50,100, 150,250,750, 1000	3,12,15,30,75 90,120,150, 300,450,600, 750,900,1200	7.0,8.75,11.0, 16.5,28	10.5,26,47,87.5
	Layouts	Rectangular lots Frontage/depth Frontage 64/100 Block sizes vary with lot size.		a) 8-20 acre blocks b) 16-10 acre blocks	Five laterals one submain per cell	Single family conventional Single family clustered Town house Low rise apartments High rise apartments Planned mix	Conventional single family medium density planned unit development High density PUD High rise apartments
Site Characteristics	Slope	Flat	Flat	Flat	a) Flat b) Minimum for flow at 2 ft/sec.	Flat	Flat moderate (2-12%) steep (> 12%)
	Soil Conditions	Average	"Easy Trenching"	Common Earth	Common earth Sand Gravel Silt Clay Shale Bedrock High Water Table	Common earth	Loam Sand Loose gravel Compacted gravel and till Hard clay and shales

Table 6-1 (continued)

		Urban Land Institute	Downing	Dajani and Gemmell	Howe	RERC	Meta
Cost Data	Base	Boston, Aug. 1955	1957-1959	(1957-1959)?	1970	1973	National average, mid 1975
	Pipe Costs	8" \$8/ft 12"-15" \$12/ft	From Greely & Hanson*	$\$/ft=1.403 + 1.4990^2 + .019X^2$ D = Dia. X = Depth	Dodge Estimating Guide** Calculated pipe and excavation costs separately	8" \$8.22/ft 15" \$14.52/ft 30" \$26.69/ft	Dodge Estimating Guide**
	Manhole Costs	Included in pipe costs	\$230	Not included	\$500 for sewers $\leq$ 36" \$1500 for sewers > 36"	\$500	Dodge Estimating Guide**
Design Data	Per Capita Flow (GPCD)	100	75	100	100	100 +	100
	Peak Flow/ Average Flow	-	3.0	$\frac{5}{P^{1/5}}$ $1 \leq P \leq 412$ P = pop. in thousands	$\frac{5}{P^{1/5}}$ $1 \leq P \leq 1000$	-	$\frac{5}{P^{1/5}}$ $1 \leq P \leq 412$
	Minimum Depth to Invert	-	10' Average Depth	5'	8'	-	5'
	Minimum Pipe Diameter	8" used for all collectors - 12"-15" used for all submains	8"	8"	8"	70% 8" pipes 20% 15" pipes 10% 30" pipes	8"

Table 6-1 (continued)

		Urban Land Institute	Downing	Dajani and Gemmell	Howe	RERC	Meta
Design Data (continued)	Manning "N"	-	.012	.013	.013	-	.013
	Minimum Velocity (ft/sec)	-	2	2	2	-	2
	Maximum Velocity (ft/sec)	-	10	10	10	-	10
	Slope Requirements	-	-	-	Ten states standards***	-	Metcalf and Eddy+
	Pumping	No	No	No	When depth exceeded 30'	-	When depth exceeds 20'
	Manhole Spacing	-	300'	-	220'	300'	350'

* Greely and Hansen Engineers, Madison, Wisconsin Sewer District Report on Sewerage and Sewage Treatment, Chicago, 1961.

** Dodge Estimating Guide for Public Works Construction - 1970 Annual Edition No. 2, New York, McGraw Hill Information System Company, 1970.

*** Committee of the Great Lakes - Upper Mississippi River Board of State Sanitary Engineers, Recommended Standards for Sewage Works - 1968 Edition, Albany, Health Education Service, 1968.

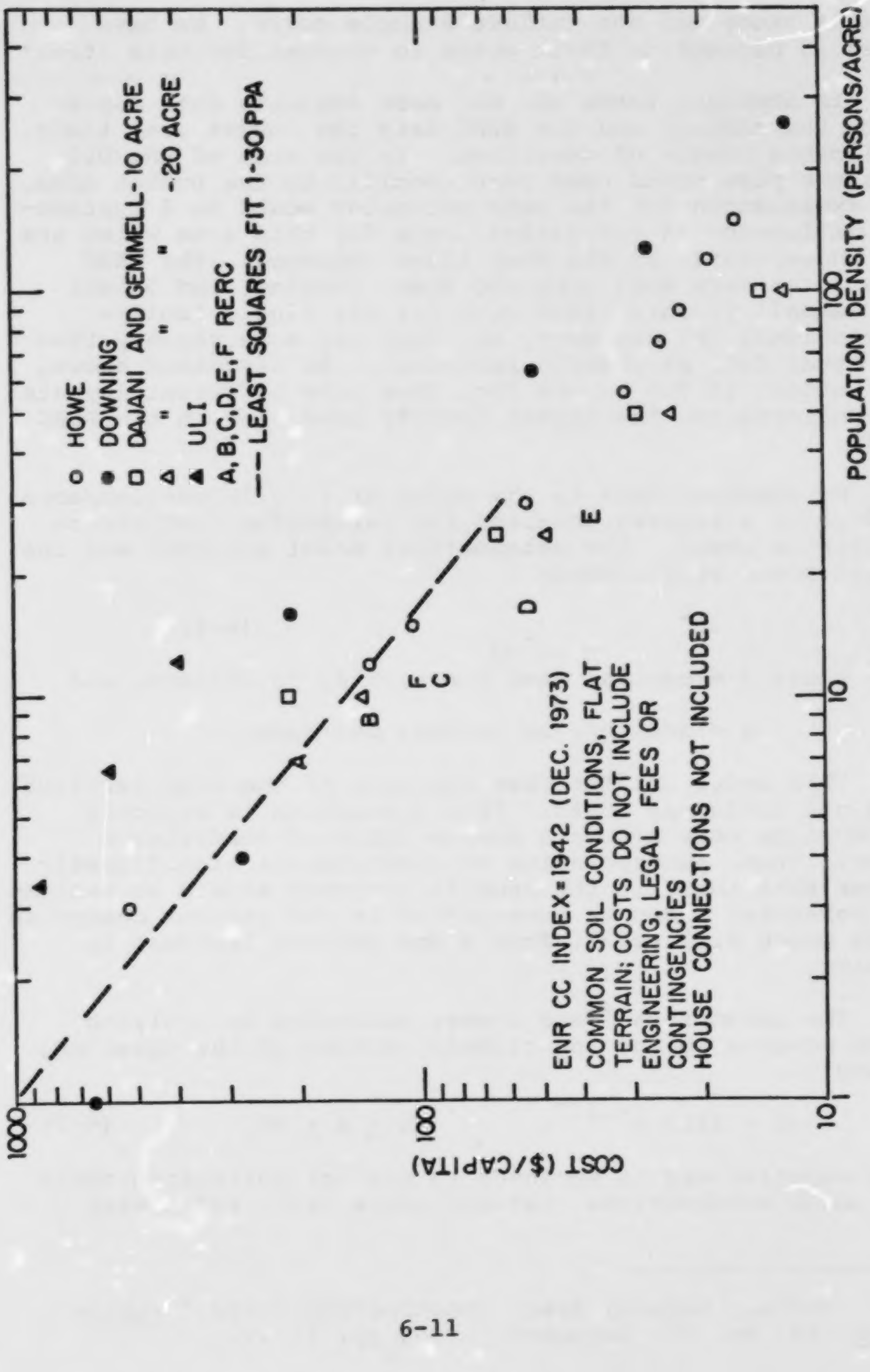
+ Metcalf and Eddy, Wastewater Engineering, New York: McGraw Hill, 1972.

street patterns and clustering of units, where appropriate. The ULI study, which was done in 1957, employed a rectangular grid system but adjusted street spacing and lot geometry with density in a realistic manner. Dajani and Gemmell and Howe, on the other hand, ignored issues of layout and employed fixed collection grids. Dajani and Gemmell calculated costs for two sets of grids, one based on 10-acre rectangular blocks and a second using 20-acre blocks. Although there were significant cost differentials between the two sets of designs, the authors did not discuss the circumstances under which one or the other of the patterns would be appropriate. Downing's presentation does not allow any conclusions about his treatment of the layout issue except that he, too, used a rectangular street grid.

In the actual design and cost estimation of the sewer network the situation is reversed. The ULI and RERC studies paid no attention to the actual system design. They merely estimated the total length of pipe in the system and applied average coefficients of cost per foot to calculate total costs. Both Dajani and Gemmell and Howe produced detailed hydraulic designs for each sewer system considered and used these designs as a basis for cost estimation. Downing's analysis was somewhere between these two approaches in degree of detail.

Most of the studies were concerned with systems where trenching conditions are favorable and topography is either flat or gently sloping. Only Howe considered a variety of soil conditions in his analysis. He also employed two different types of topography, flat and favorable (i.e., slope which requires the minimum of excavation). However, Howe's layout probably was the least satisfactory of all the designs.

Figure 6-1 compares data from all five studies which we reviewed. We have attempted to make these data as comparable as possible by adjusting all costs to December, 1973 and adjusting the data, where necessary, to add or exclude cost components so that all data refer to a common set of assumptions. We have excluded engineering fees, legal fees, contingency costs and house connection costs. All data refer to common soil conditions and flat terrain. In one case, the Dajani and Gemmell study, the original cost data were not available. Instead we used costs generated by equations fit to their data. These costs have been estimated for densities corresponding to the original networks employed in the study. Also, the Dajani and



WASTEWATER COLLECTION COSTS-SUBDIVISIONS

Figure 6-1

Gemmell study did not include manhole costs. We have added 15 percent to their costs to account for this item.*

In absolute terms the ULI cost estimate data appear to be the highest and the RERC data the lowest over their applicable ranges of densities. In the case of the ULI data the pipe costs used were specific to the Boston area. One explanation for the high estimates would be a systematic difference in excavation costs for this area which are not incorporated by the cost index employed. The RERC data agree very well with the Howe, Downing, and Dajani and Gemmell 20-acre block data for its single family-conventional (A) category, but drop off more rapidly than the other data as density increases. As discussed above, this effect is due to the fact that more efficient layouts are employed for the higher density land uses in the RERC study.

We employed data in the range of 1 to 30 persons/acre to develop a general equation for estimating subdivision collection costs. The mathematical model employed was the simple power relationship

$$c = ad^{b} \qquad (6\text{-}1)$$

where c = capital cost per capita, in dollars, and

d = density, in persons per acre.

This model assumes that the size of the area serviced does not influence costs. This assumption is strictly appropriate only within a narrow range of subdivision sizes. Thus, extrapolation to subdivisions significantly larger than those in the studies reviewed should be avoided. The parameter b can be interpreted as the percent change in costs which will result from a one percent increase in density.

The parameters a and b were estimated by applying least squares to the logarithmic version of the equation, giving

$$C = 1050\ d^{-.827}, \qquad 1 \leq d \leq 30. \qquad (6\text{-}2)$$

This equation may be employed to predict collection costs for small subdivisions (100-200 acres) with relatively favorable trenching conditions and level topography. It also may be possible to employ the Howe data as a basis for adjusting this equation to handle other soil conditions.

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* J. Baffa, "Lateral Sewer Construction Costs," Public Works, 86, No. 11, November, 1955, pp. 71-77.

In summary, of the five studies reviewed, none appears to be completely adequate to serve either as a sole source of data or a prototype for a more general model. Two of the studies (ULI and RERC) were conducted by planners and emphasize the development layout but treat the engineering and the cost estimations of collection networks rather casually. Two other studies, conducted by engineers (Dajani and Gemmell, Howe), use development layouts which are unrealistic for current suburban subdivisions but take great care with system design. The fifth study, by an economist (Downing), falls between the two extremes. Only one study, Howe's, considers a realistic variety of soil conditions, but this work has one of the least representative layouts. All the studies focus on the development (subdivision) level of costs.

Interceptor Level Costs. Interceptors link new development with the existing sewer network. Their costs, requiring a different set of calculations, have traditionally been computed on the basis of relationships such as: dollar/mgd/mi. = f (average flow at ultimate capacity). Various cost functions such as Spencer's are common.* The question of ultimate capacity has to be determined by the planner by investigating various projections of additional development in the same area. The appropriateness of cost functions such as Spencer's, which is a simple 1958-based power function updated by the ENR Index, might be questioned if it happens that not only inflation but also changes of practice influence the actual cost. But the function seems to be satisfactory as a first approximation.

Modeling Stormwater Collection Costs

Stormwater collection costs are much more difficult to characterize than those for wastewater. Unlike the latter case, there are few generally accepted design rules for handling stormwater design problems. Ardis, Denker, and Lenz have documented the divergence of design practices in their study of 32 cities in Wisconsin.* Despite the geographically limited data base, the authors found great variation in procedures employed by local public works departments. For example, consider the frequency of the design storm. The design storm is the storm which the system would just barely handle. Thus a five-year design storm implies that, on the average, once in five years gutters will overflow, storm sewers will back up and localized flooding will occur in basements and other structures. Obviously the selected frequency will have an important effect on overall system costs. Since loss of life is generally not an issue in the type of minor flooding we consider here, the frequency selected represents a balance between cost and the potential property damage and inconvenience which would be caused by minor flooding. The frequencies employed by the 32 cities reporting in the study ranged from one to 25 years.

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* C. C. Spencer, "Metropolitan Planning for Sewers on a County Basis," *Public Works*, 89 (8), August, 1958, p. 83: Cost/mi. = $46{,}000\ (\mathrm{mgd})^{-.45}$; the equation is based on an ENR-construction index of about 1,000.

In another part of the study, respondents were asked to design a stormwater collection system for a hypothetical 15-acre area located in their jurisdiction. The results of this exercise again demonstrated the great variability in design procedures. Although all designs were for an identical tract of land, the most expensive design differed from the least expensive by a factor of about six.

Two of the cost studies described in the previous section, the ULI study and the RERC study, also considered storm sewer costs. However, these studies used "average" coefficients of cost per foot in developing their estimates and made no effort to indicate the effect on these costs of soil, climate, topography or design standards. In fact, they did not even fully describe the conditions under which the estimates would be applicable. As a result, these studies are not useful models for estimating stormwater collection costs.

Rawls and Knapp** have made an empirical study of stormwater collection costs. Their sample included designs for tracts of land ranging from 11 to 1,485 acres. Based on a sample of 70 projects they developed the following equation for estimating stormwater costs in 1963 national average prices:

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* C. V. Ardis, J. Denker, and A. T. Lenz, "Storm Drainage Practices of 32 Cities," J. Hydraulics Division, American Society of Civil Engineers (ASCE), Vol. 95, January, 1969, pp. 383-408.

** W. J. Rawls and J. W. Knapp, "Methods for Predicting Urban Drainage Costs," J. Hydraulics Division, ASCE, Vol. 38, September, 1972, pp. 1575-85.

$$C_T = 58{,}273.0 + 8.73(F^{0.04}S_G^{-.89}R^{0.64}D_B^{0.23}Q^{0.73}A_D^{0.71}),^* \qquad (6\text{-}3)$$

where:

C_T = Project Cost, in 1963 dollars,

F = Recurrence Interval, in years,

S_G = Average Ground Slope, in feet per 100 feet,

R = Runoff Coefficient, C from rational method,

D_B = Smallest Pipe Size, in inches,

Q = Total Capacity, in cfs,

A_D = Developed Area, in acres.

From a planning standpoint it would have been better if the total capacity had not been included in the estimation, since it would then have been possible to estimate costs from engineering practices and natural features without resorting to detailed calculations.

Another factor to consider in stormwater management is the use of on-site storage or infiltration systems. Traditional approaches to stormwater management have emphasized removal of the water from the site as rapidly as possible. This approach tends to make matters progressively worse downstream since it reduces the times of concentration, resulting in higher downstream peak flows. Recently, more emphasis has been given to on-site storage as a method of reducing peak flows. For many areas a combination of storage and smaller storm sewers will be economically superior to the sole use of large storm sewers. A variety of methods for providing the necessary storage currently are being tried. These include roof storage, parking lot storage, and permanent or temporary ponding. The latter method appears to be favored in suburban residential areas.

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* The R^2 is equal to 0.785.

Since the trend toward on-site storage is relatively recent, there has appeared no systematic cost analysis suitable for planners. For suburban residential areas, some guidance may be obtained from Maryland's experience with sedimentation basins. These basins are similar to storage basins except they are designed to be temporary facilities for use during construction (many silt basins are, in fact, converted for stormwater storage after construction is completed). The APWA* reports that sedimentation ponds in Maryland cost about $50-70 per house lot. The APWA also reports data for an Illinois development where detention ponds cost about $100-300 per residential lot for lot sizes up to 1/2 acre.

Cost Evaluation Module: Models Developed and Selected

Introduction

This section deals with the cost impact module derived from the foregoing review of the water-related system models. When treating development and cost impact, we arrive automatically at "intertemporal" aspects. Limited resources have not permitted a truly intertemporal model, so we offer a comparative model instead. We assume that the planner establishes a base year for data -- say 1974. This data base is modified according to projections the planner wishes to examine. The model provides estimates of impacts, costs, cost breakdowns, and thereby establishes incidences for comparative analysis of the base and the projected year. Decisions are predicated on a series of such comparisons.

There exists a difference between comparative physical and economic analyses. Physical analysis simulates total residuals and water quality impacts for events drawn from the base and projected years. Economic/financial analysis estimates additional costs (and their breakdown) due to changes between the base and projected year.

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* American Public Works Association (APWA), "Practices in Detention of Urban Stormwater Runoff," Special Report No. 43, 1974.

The financial/economic module presented operates only on single communities, but it should also be capable of analyzing parts of the community. It concentrates on residential development in the urban fringe area. The following costs are considered:

1. Sanitary sewer laterals in the development and house connections;
2. Drainage system for the development (including temporary and permanent retention basins);
3. Interceptors to link the new development with the existing sanitary sewer system;
4. Construction of relief sanitary sewers in case of inadequate capacity of the existing system;
5. Expansion of the wastewater treatment plant, required when the additional flow and load overload the treatment plant capacity;
6. Adjustment for additional runoff of man-made and/or natural stormwater drainage system; and
7. Treatment of additional runoff to improve runoff quality.

Based on these cost categories, the following eight cost types j can be estimated by the cost evaluation module for each proposed development:

$j = 1$ on-site disposal

$j = 2$ sanitary sewer laterals

$j = 3$ sanitary sewer building connections

$j = 4$ sanitary sewer mains/trunks

$j = 5$ storm sewer laterals

$j = 6$ stormwater detention ponds

$j = 7$ storm sewer mains/trunks

$j = 8$ sewage treatment plant

Each cost type j is divided into a cost function for capital costs (CC_j) and operating and maintenance costs (OM_j).

In the following sections the cost functions employed will be described. Capital costs for sanitary sewer laterals have been estimated in the course of the project, and their development will first be outlined in some detail. Cost functions related to cost types j = 1, 4, 5, 6, 7 and 8 are described later in the section.

Sanitary Sewer System Cost Estimates

Up to the present time there has been no generally adequate, simple model available for estimating sanitary sewer system costs at the level of detail required by the planner. Such a model, which would be applicable for a variety of common soil types, slope conditions, and development patterns, has been developed in two major stages. First, ten hypothetical subdivisions and associated lateral sewer systems were designed or adapted from available sources. Sewer costs were then estimated and synthesized into a number of simple equations for producing generalized cost estimates.

Review of Costs Factors. Four key factors were taken into account in the analysis: (1) the types of housing and subdivision design; (2) physical design of the sewer system; (3) soil types; and (4) topography. Each factor is discussed below.

(1) Housing Types and Subdivision Design. Six basic types of housing units were included in the analysis. These were selected to be representative of the types of housing found in new developments in urban fringe areas. A short description of each of these types follows:

A. Single-family conventional -- traditional single family homes in moderate sized lots which vary in size from 1/4 to 1/3 acre.

B. Single-family compact -- single family homes on small lots of about 1/8 acre.

C. Townhouses -- attached two-story units in configurations of four to eight units per structure. Each townhouse unit has a separate sewer connection.

D. Garden apartments -- three-story walk-up apartment buildings with an average of 30 units per building.

E. Medium-rise apartments -- five-story elevator apartment buildings with an average of 100 units per structure.

F. High-rise apartments -- 20-story apartment buildings, 500-900 dwelling units per building.

Various combinations of these six types of housing were employed to develop a set of ten subdivision layouts for detailed sewer design and cost evaluation. For each subdivision, designs were evaluated for three different soil categories: (1) loose sand, loam and gravel; (2) compacted gravel and till; and (3) hard clay and shale. Thus a total of 30 cost evaluations were completed. The soil categories were based upon the categories of the _1975 Dodge Guide_,* which was the basis for all cost estimates.

Table 6-2 summarizes the ten subdivision designs employed in our study. Each design is characterized by its mix of dwelling unit types and average slope conditions. The basis for the three slope classifications (flat, moderate, steep) will be covered fully in a later subsection on physical design.

It has been our intention, in selecting layout patterns for detailed analysis, to adequately reflect the diversity of the suburban housing market. Our designs therefore include subdivisions consisting entirely of conventional single-family homes at one extreme and entirely of 20-story apartments at the other, while the majority of cases include various mixes of dwelling units. In all cases layouts have been selected to be representative of current practice in the industry. The subdivisions ranged from 160 to 205 acres in size, this scale being selected for compatibility with our 160-acre grid employed as a data base. This size also was judged to be large enough to allow for the evaluation of complete developments while at the same time small enough to allow for a reasonable number of designs to be examined with our limited resources.

A variety of sources were employed to select appropriate layouts. Design 1 is an actual development constructed in the town of Clay, New York, with some minor modifications. Designs 5 and 7 are based on design studies by the New York

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* _Op_. _cit_.

Table 6-2

Summary of Subdivision Designs

Design	Area (acres)	Slope	Number of Dwelling Units						Gross Density DU/acre
			Single Family Conventional	Single Family Compact	Town Houses	Garden Apartments (3-story)	Medium-Rise Apartments (5-story)	High-Rise Apartments (20-story)	
1	180	Flat	540	---	---	---	---	---	3.0
2	160	Moderate	471	---	---	---	---	---	2.9
3	160	Steep	471	---	---	---	---	---	2.9
4	160	Flat	359	---	652	207	---	---	7.6
5	205	Moderate	---	553	619	396	---	---	7.6
6	160	Steep	367	---	590	300	---	---	7.8
7	160	Flat	---	300	276	540	1040	---	13.5
8	205	Moderate	---	359	417	696	1290	---	13.5
9	160	Moderate	---	227	233	576	1120	---	13.5
10	160	Flat	---	---	---	---	---	4000	25.0

City Planning Department.* The remainder of the designs were developed by our own staff and represent extrapolations of patterns found in Massachusetts, New York and Connecticut. A representative layout (design 1) is depicted in Figure 6-2 with a ten-acre grid overlaid to indicate the scale.

(2) Physical Design. The procedures employed in the design and cost estimation of the sanitary sewer systems were much the same as those which would be used by a design engineer in the preliminary analysis of such systems. We began with a tentative network configuration, including locations of pipes and manholes. Detailed hydraulic design was then undertaken for each link in the network. The end result of this procedure was a detailed specification for each link, including upstream and downstream invert elevations, peak flow and velocity, and total amount of excavation and sheeting required. These specifications then formed the basis for calculating total system costs.

No excess capacity was deliberately designed into the system, although some pipes in the system do have such capacity as a result of standards on minimum pipe size and other restrictions. This approach implies that there is no allowance for the "linking" of subdivisions. We assume that a series of interceptors and mains will be provided for this purpose. Such "higher order" collectors are generally provided by the local or county government and the costs for these must be added to the collection costs computed for one subdivision. Also, our approach assumes no significant change in land use. At one time it was common for engineers to design collection systems for the highest density which they thought might develop in the life of the system, usually 50 to 100 years. With the implementation of effective residential zoning policies, engineers recognized that such conservative design procedures no longer were required. Today the capacities of most sewer systems in suburban areas are based upon the existing zoning policies.

The influence of the various engineering standards on system costs have been discussed previously.** Here, we

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* New York City Planning Department, Planned Unit Development, May, 1968.

** "Data Collection and Review and Analysis of Infrastructure Cost Relationships," Working Paper No. 3, prepared for the Environmental Protection Agency by Meta Systems Inc under Contract No. 68-01-2622, February 15, 1975.

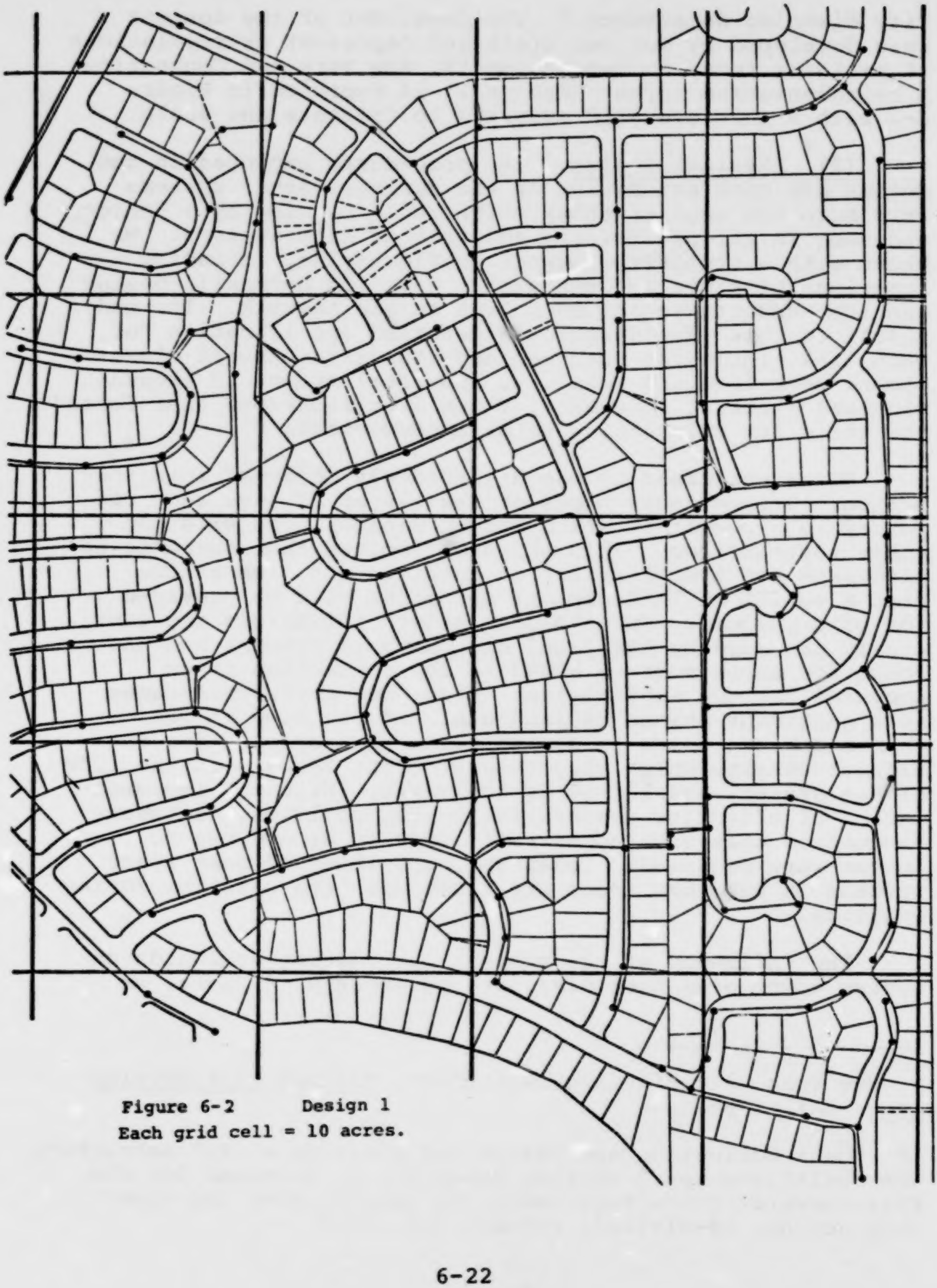

Figure 6-2 Design 1
Each grid cell = 10 acres.

shall only summarize the standards employed in this design study. The standards selected were based upon recommendations in the American Society of Civil Engineers/Water Pollution Control Federation joint committee manual,* and textbooks by Metcalf and Eddy** and Babbitt,*** unless otherwise specified.

1) Number of persons per dwelling unit = 3.5 (from Costs of Sprawl† assumption for single family homes).

2) Flow per capita = 100 gallons per day.††

3) Ratio of peak to average flow, $\frac{Q_p}{Q_a}$:

$$\frac{Q_p}{Q_a} = \frac{5.0}{p^{0.2}} \qquad (6\text{-}4)$$

where p = population served, in thousands.

4) Equation for flow -- Manning's Equation

$$V = \frac{1.43}{n} R^{2/3} S^{0.2} \qquad (6\text{-}5)$$

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* Design and Construction of Sanitary and Storm Sewers, American Society of Civil Engineers and the Water Pollution Control Federation, New York, 1970.

** Metcalf and Eddy, op. cit.

*** H. E. Babbitt and E. R. Baumann, Sewerage and Sewage Treatment, 8th edition, New York: John Wiley and Sons, 1958.

† Real Estate Research Corporation, op. cit.

†† In the past, the Environmental Protection Agency has accepted 100 g/cap/d as a standard design value (see "Interceptor Sewers and Suburban Sprawl," prepared for Council on Environmental Quality by Urban Systems Research and Engineering, Inc., Cambridge, Massachusetts, September, 1974, under contract EQ4AC027); this value is currently being reconsidered.

n = coefficient of roughness = .013 by assumption

R = hydraulic radius, in feet

S = slope in ft/ft.

5) Minimum velocity for pipe flowing full = 2 ft/sec. Maximum velocity for pipe flowing full = 10 ft/sec.

6) Minimum slopes:

diameter (inches)	slope (ft/ft)
8	.004
10	.003
12	.0022
15	.0015
18	.0012
21	.001
24	.0009
≥27	.0008

7) Minimum pipe diameter: street laterals = 8"; House connectors = 6".

8) Minimum depth to invert = 5 feet.

9) Manhole spacing. Maximum spacing = 350', on curved sections wherever pipes join at an angle >2°.

10) Sheeting, bracing and trenching. Trench designs were developed to conform to the requirements of the Federal Occupational Health and Safety Act. This legislation has had a significant impact on sewer costs, since it requires a greater use of sheeting and bracing than had been common previously. Design varied with soil types, which were divided into the general categories cohesive and non-cohesive, as specified below:

max. trench depth	cohesive	non-cohesive
0-6'	vertical trench	sides sloped at 2:1 ratio
6-10'	vertical trench; skeleton bracing	full sheeting and bracing
>10'	vertical trench; full sheeting and bracing	full sheeting and bracing

Minimum trench widths were 3'.

11) Pipe materials. Vitrified clay pipes were employed in all sections of the system.

(3) Soil Types. All subdivisions are designed for three soil classifications. These classifications were taken from the Dodge Guide,* which established the categories as a basis for cost analysis. The three categories were: loose sand, loam, and gravel; compacted gravel and till; and hard clay and shales. The first two were considered to be non-cohesive, the third cohesive for trench design per (10) above.

(4) Topography. There is a relatively broad range of slopes over which pipes can be placed at minimum depth. As a result, we have not considered a large number of slope conditions in this study. Rather, we have dealt with three categories of topography. Our flat topography category includes land where average slopes are too small to allow sewer lines to be laid at minimum depth. These include slopes in the range 0-0.5 percent. The moderate slope category includes slopes which allow most of the collectors to be placed at minimum depth and is therefore the most favorable condition. This category includes slopes from 0.5 to 11 percent. Finally, the steep slope category includes slopes which are too severe to allow placement of lines at minimum depth and includes slopes from 11 to 16 percent. The divisions between slope categories should not be considered as exact. They represent our best estimates based on the experience gained in evaluating our ten project designs, but some fuzziness is inevitable in any such classification scheme. Depending on particular conditions,

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* Op. cit.

the range of favorable slopes could be somewhat greater or smaller. However, we feel that in most instances the classification of a particular area should be straightforward.

All the designs which were evaluated had either uniform or only slightly varying slopes over the extent of the development. As a result, our cost estimates are not strictly applicable to cases where the terrain is highly irregular. We hypothesize that our estimates for the flat or steep slope categories (the two sets of estimates are quite close) could be employed as a first approximation to estimate the costs for irregular topography, which is also an unfavorable condition from the standpoint of sanitary sewer costs.

Costs for the systems based on the combinations of layout and engineering designs, soil and topography were synthesized from unit costs for pipe sections, connectors, manhole sections and covers, excavation, fill and sheeting. All unit costs were obtained from the Dodge Guide* and are expressed in national average prices, mid-1975. A detailed presentation of these cost estimates, including the proportions of total cost allocated to each major component (excavation, pipe, etc) is found in Appendix F (Lateral Sewer Cost Estimates) to this report. In the paragraphs below we discuss our efforts to synthesize these results into a set of cost estimation equations for both connections and lateral sewer lines.

Sewer Connection Cost Estimates (CC_3). The setback, or distance from the dwelling unit structure to the curb is a primary factor in determining the overall cost of house connections. The setback, in turn, is generally determined by the minimum standards set by a local community through its subdivision ordinances or building codes. Since the minimum requirement can vary widely from community to community we have decided to develop cost estimation techniques separately for the house connections and the remainder of the collection system.

The general form of the equation for estimating the costs of house connections is:

$$C_{ijk} = a_{ijk} + b_{ijk}x \qquad (6\text{-}6)$$

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* Op. Cit.

where:

C_{ijk} = total cost per connection, in dollars

a_{ijk} = constant term

b_{ijk} = coefficient which reflects effect of distance with cost

x = setback distance, in feet

i = index of dwelling unit type

j = index of slope type

k = index of soil type

Thus to determine the total connection costs for an entire subdivision, one calculates the individual connection costs for each dwelling unit type in the subdivision and multiply each such cost figure by the appropriate number of connections. Note that the number of connections are identical with the number of dwelling units only in the cases of single family homes and townhouses. For apartments, we assume that each building has one connection, thus the number of connections equals the number of dwelling units divided by the average number of dwelling units per building.

It was possible to reduce the number of equations required by aggregating several of the housing type categories. The type of connection employed for conventional single family homes, single family compact, and townhouses is identical. Thus one set of coefficients can be applied to all three housing unit types. Similar comments apply to the garden apartment and medium-rise apartment categories. Also we have found that costs in the "loose sand, loam and gravel" and "compacted gravel and till" categories were virtually identical. As a result, we have replaced them with a single category, which we term "loose soils." "Hard clay and shales" remains a separate category and will be abbreviated as "clay" soils.

The coefficients a_{ijk} and b_{ijk} were computed by taking average costs for connections of each type for each subdivision where such connections were employed, then averaging over the individual subdivision estimates. The constant coefficient a_{ijk} represents the cost of the connection to the lateral plus any associated special piping and elbow sections. The coefficient b_{ijk} was calculated by dividing the remaining connection costs by the setback. Table 6-3 presents the coefficients for equation (6-10) for each appropriate combination of dwelling unit type, soil condition, and slope.

The slopes given in Table 6-3 apply only to situations where the sewer connections are installed as part of the original development, in conjunction with the system of laterals and mains. This method produces considerable economies, since connecting sections (t and y sections) can be installed as part of the original network, re-excavation of the laterals can be avoided, and it is not necessary to break through and replace sidewalks and road surfaces. If the connections are made after development, experience indicates that they will be considerably more costly and the data in Table 6-3 would not be applicable.

Lateral Sewer Costs Estimates (CC_2) Table 6-4 summarizes the results of our cost estimation procedures for the designs listed in Table 6-2. The costs presented in Table 6-4 include all collection system costs except building connections, which have been dealt with in the previous section. We shall refer to these estimates as "net costs." As in the case of house connections, there was virtually no difference between the two soil categories, "loose sand, loam and gravel," and "compacted gravel and till." Again, these have been combined into a single "loose soils" category in all analysis described below.

We experimented with a number of functional forms in attempting to develop an equation for predicting net costs as a function of the dwelling unit mix, soil type, and average slope for a development. The form which we finally settled upon is:

$$\text{NET COST} = \alpha_{k\ell} \sum_{i=1}^{5} b_{ki} N_i, \qquad (6\text{-}7)$$

where:

$\alpha_{k\ell}$ = correction factor for slope type ℓ in soil type k,

b_{ki} = cost per unit of dwelling type i in soil k,

Table 6-3

House Connection Cost Coefficient

		a_{ijk} Slope			b_{ijk} Slope		
Dwelling Unit	Soil Type	Flat	Moderate	Steep	Flat	Moderate	Steep
single family conventional, single family compact and townhouse	loose	73.73	37.59	52.66	3.45	3.45	3.45
	clay	73.73	37.59	52.66	3.15	3.15	3.15
garden apartments and medium rise apartments	loose	82.34	37.59	67.09	4.13	4.13	4.13
	clay	82.34	37.59	67.09	3.83	3.83	3.83
high rise apartments	loose	568.0*	437.90*	568.0*	7.19	7.19	7.19
	clay	568.0*	437.90*	568.0*	6.80	6.80	6.80

* High rise apartments assumed to be connected at manholes.

Table 6-4

Summary of Collection System Capital Costs*

		Cost		
Design	Slope	Loose Sand, Loam and Gravel	Compacted Gravel and Till	Hard Clay and Shales
1	Flat	969,200	970,000	701,500
2	Moderate	205,700	206,600	165,600
3	Steep	467,900	469,100	371,900
4	Flat	963,200	964,300	658,800
5	Moderate	334,400	335,500	232,900
6	Steep	988,300	989,800	812,200
7	Flat	836,100	837,100	610,100
8	Moderate	302,800	303,700	213,000
9	Moderate	281,800	282,500	209,300

* Costs do not include house connections, engineering and legal fees, or contingencies. Costs are in mid 1975 dollars, national average.

N_1 = number of units of conventional single family homes,

N_2 = number of units of clustered single family homes,

N_3 = number of units of townhouses,

N_4 = number of garden apartment buildings,

N_5 = number of medium-rise apartment buildings,

ℓ = 1-flat; 2-moderate; 3-steep,

k = 1-clay; 2-loose.

We omit the sixth dwelling unit type, high-rise apartments, because it was only used in one design and therefore was not included in our parameter estimation procedures.

The mathematical model assumes that the effect on costs of an additional dwelling unit is linearly additive. That is, a dwelling unit of type i will add $\alpha_{k\ell}b_{ki}$ to the total system costs regardless of the number and type of other units in the subdivision and the relative location of different types of units. A little reflection quickly reveals that this assumption is not strictly valid. For example, an apartment complex located at the upper reaches of a collection network might require large size pipes in the downstream links in the subdivision, while the same complex located at the end of the system will only affect the size of the final link. The total costs in the two cases will generally not be the same. Thus the spatial allocation of dwelling unit types within a development does affect system costs, contrary to the model assumption. However, we did not have enough data to include such detailed effects in the model. In addition, in many situations the planner would not have information available on the detailed location of different housing types when he is to make his evaluation. Consequently, the model developed here is intended to reflect average costs from typical layout patterns.

An additional note of caution is warranted with respect to subdivision size. As Table 6-2 indicates, all of our designs have been for 160-205-acre developments. Sewerage costs increase nonlinearly with area: for any given density, the larger the area serviced the greater will be the per unit costs. Thus our model will tend to overpredict costs for developments significantly smaller than those considered in this study and underpredict costs for significantly larger developments.

Since equation (6-7) has seven parameters and the sample includes nine designs, the parameters could be evaluated directly by applying nonlinear estimation procedures using a criterion such as minimization of the sum of squared differences between actual and predicted project costs. However, because of the small sample size we have chosen to employ a more robust, heuristic approach in our initial analyses. This procedure was based upon the criterion of minimizing the sum of absolute deviations between observed and predicted costs.

The resulting equations were:

Hard Clays and Shale:

$$\text{Cost} = \alpha_{1\ell}\,(352N_1 + 216N_2 + 101N_3 + 3620N_4 + 6656N_5) \qquad (6\text{-}8)$$

$\alpha_{11} = 2.8$

$\alpha_{12} = 1.0$

$\alpha_{13} = 2.7$ $\qquad R^2 = 0.82$

Loose Soil:

$$\text{Cost} = \alpha_{2\ell}\,(437N_1 + 259N_2 + 191N_3 + 5190N_4 + 8290N_5) \qquad (6\text{-}9)$$

$\alpha_{21} = 2.8$

$\alpha_{22} = 1.0$

$\alpha_{23} = 2.7$ $\qquad R^2 = 0.85$

The R^2 value indicates the proportion of the variance which is explained by the model. Since we minimized absolute rather than squared deviations the parameter estimates did not optimize upon the value of R^2. Nevertheless, the value of R^2 is useful in judging the explanatory power of the model. In both cases it signifies that substantial amounts of unexplained variation remain unaccounted for. This is due to the variety of different layouts employed in our design studies.

Another way of evaluating the model results is to check the consistency of the parameter estimates with commonly accepted rules of thumb. For example, rough estimates of sewerage costs often are based on lot frontage because for small pipe sizes, the most significant costs are associated with total system length (pipe length, sheeting and excavation, number of manholes) rather than capacity. By this criterion the relative costs of sewering single family conventional, single family clustered and townhouses should be approximately in the ratios 80/50/25 respectively, which are their average frontage, in feet. Simplified, these ratios become 1/0.625/0.3125. From equation (6-17), the associated ratios are 1/0.61/0.29 which agree closely with the hypothesized relation. Equation (6-9) gives ratios of 1.0/0.59/0.43; the townhouse costs are somewhat more expensive relative to single family conventional units than for equation (6-8).

As with the case of house connections, the costs cited here apply only where sewers are installed with the original components which must be added to establish a realistic cost estimate. These components are generally listed as "engineering, legal fees and contingencies" in consultants' estimates and account for approximately a 25% additional charge to the base estimate. Finally, in areas with extensive bedrock formations close to the surface or a high water table, costs would be significantly greater than predicted by equations (6-8) or (6-9).

Stormwater Laterals (CC_5)

Because of the lack of unified design standards for stormwater management, it was not possible to develop a useful model for estimating these costs along the lines of our sanitary sewer cost evaluation. For comparative purposes, we have evaluated the costs for designing a stormwater collection system for subdivisions 2, 5, and 8 of Table 6-2, employing the 25 year design storm recommended by the engineering department of the Town of Hamden, Connecticut.* The resulting costs were:

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* Drainage Manual, Town of Hamden, Connecticut, Hamden Engineering Department, July, 1971.

Subdivision	Loose	Clay
2	$529,000	$556,000
5	$954,000	$897,000
8	$863,240	$797,000

Thus the costs of the stormwater collection system is about 2.5 - 3 times that of the sanitary sewers. However, the 25 year storm is an unusually high design standard, and no general conclusions could be made on the basis of the results. In our model we have employed the equation estimated by Rawls and Knapp (see above) to estimate stormwater collection cost.

Other Cost Functions

The capital cost functions for cost types j = 2, 3, 5 were discussed in preceding sections. The others will be input as follows:

On-site disposal:

$$CC_1: \quad C = 125. + .15\ (V-500) + CLF^* \qquad (6\text{-}10)$$

where:

CC_1 = delivered tank cost

V = net volume of the tank in gallons

CLF** = cost of associated leaching field.

V is calculated from:***

---

* "On-site Household Wastewater Treatment Alternatives -- Laboratory and Field Studies," R. J. Otis, N. J. Hutzler, W. C. Boyle, in Water Pollution Control in Low Density Areas, edited by W. J. Jewell and R. Swan.

** Because of regional variations in labor and material costs, this variable which describes mainly the excavation of trenches to be filled with gravel, has to be estimated and input by the planner on a case by case basis.

*** Manual of Septic Tank Practice, U.S. Department of Health, Education and Welfare, Public Health Service, Publication No. 526, Reprinted 1969.

$V = 1.5\ Q$ for $Q < 1500$ gallons wastewater per day

$= 1125. + .75\ Q$ for $Q \geq 1500$ gallons wastewater per day (6-11)

an installation cost of $275 is assumed.

OM: assumes one pumping every three years at a cost of $30 per pumping or $10/year.*

Sanitary sewer laterals:**

OM_2: $C_H = .236\ell$*** (6-12)

where:

C_H = annual per household cost

ℓ = feet of sewer per capita and,

$\ell = 54X^{-.65}$ (6-13)

where X = population density in persons per acre.

Sanitary sewer building connections:

OM_3 are considered negligible in this context.

Sanitary sewer mains/trunks:

---

* Ibid.

** CC_2 and CC_3, as previously noted, do not take into account the effect of industrial or commercial establishments on the collection systems costs. Similarly, OM_2 also does not.

*** P. M. Meier, J. Kühner and J. C. Martell, "A Preliminary Assessment of Wet Systems for Residential Refuse Collection," Curran Associates, Inc. (for the Environmental Protection Agency), July, 1973, Contract No. 68-03-0183, p. 203 (NITS-PB 234436).

CC_4: $\ell n\, C_4 = .07167 + (1.04284 - .006114Z)\, \ell n\, D + .06147Z$* (6-14)

C_4 = construction cost, pipe in place, in \$/ft. based on an ENR Construction Cost Index of 1975.

Z = average depth of trench, in feet

D = diameter of sewers, in inches

OM_4: average number of repairs per mile of sewer is assumed to be 2.2 per year with an average cost of \$162 per repair;** only the costs of the new system are considered.

Storm sewer laterals:

OM_5: Same as OM_2.

Stormwater detention ponds:

CC_6: \$200 - \$600 per residential acre***

OM_6: no realistic estimates available.

Storm sewer mains/trunks:

CC_7: Same as CC_4

OM_7: Same as OM_4

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* H. A. Thomas, M. Shapiro, J. Houghton, "Paretian Analysis of Regional Systems for Sewage Disposal," Discussion Paper 74-2, August, 1974, Environmental Systems Program, p. 17.

** P. M. Meier _et al_., _op_. _cit_., p. 203.

*** American Public Works Association, "Practices in Detention of U.S. Stormwater Runoff," Special Report No. 43, 1974.

Sewage treatment plant (new plant and/or capacity expansion):*

$$CC_8 = a_1x_1^{b_1}X_2^{b_2} \quad [1 + f(\psi)] \qquad (6\text{-}15)$$

$$OM_8 = a_2X_3^{b_3} \qquad (6\text{-}16)$$

where:

X_1 = design population equivalent (see below)

X_2 = design flow, mgd

X_3 = actual flow, mgd

ψ = design population (in persons)

f = ancillary works factor (dimensionless).

Values for the parameters are given in Tables 6-5, 6-6, and 6-7. The population equivalent, X_1, is obtained using the following expression:**

$$X_1 = \frac{8.33X_2C}{0.17} \qquad (6\text{-}17)$$

where:

8.33 = conversion constant (8.33 lbs/million gallons per mg/ℓ)

0.17 = lbs of five-day biochemical oxygen demand (BOD) per capita per day

C = BOD_5 of wastewater in mg/ℓ.

The detailed breakdown of the treatment plant into subprocess and the availability of the corresponding

---

* For detailed description of variables refer to: Meta Systems Inc, "Evaluation of Alternative Methods for Financing Municipal Waste Treatment Works," Socioeconomic Environmental Studies Series, Environmental Protection Agency, 600/5-75-001, February, 1975.

** Meta Systems Inc, Ibid.

Table 6-5

Parameters of Capital Cost Functions

Type	a_1	b_1	b_2
	Biological Treatment		
Activated Sludge	.00812	.461	.262
Filtration	.122	0	.656
Sludge Handling:			
Sludge Pump	.0125	0	.480
Sludge Digester	.0575	0	.650
Sludge Holding Tank	.0224	0	.590
Vacuum Filtration	.326	0	.560
Incineration	.0150	0	.560
	Physical-Chemical Treatment		
Coagulation and Sedimentation	.067	0	.890
Filtration	.122	0	.656
Carbon Adsorption			
$X_2 \leq 10$ mgd	.546	0	.613
$X_2 > 10$ mgd	.293	0	.983
Chlorination	.0202	0	.664
Sludge Handling: (as above)			

SOURCE: Meta Systems Inc, Ibid.

Table 6-6

Parameters of O&M Cost Functions

	Biological Treatment	
Type	a_2	b_3
Activated Sludge	.042	.876
Filtration	.022	.650
Sludge Handling:		
Sludge Pump	.0021	.452
Sludge Digester	.0095	.712
Sludge Holding Tank	.0015	.530
Vacuum Filtration	.063	.706
Incineration	.0089	.570
	Physical-Chemical Treatment	
Coagulation and Sedimentation	.0147	.986
Filtration	.0136	.638
Carbon Adsorption		
$X_3 \leq 10$ mgd	.1058	.483
$X_3 > 10$ mgd	.0502	.808
Chlorination	.0043	.905
Sludge Handling: (as above:		

SOURCE: Meta Systems Inc, Ibid.

Table 6-7

Ancillary Works Factor Ψ

Dependent Upon Population Size

Ψ ≤	500	but >	0	f =	0.373
	999		500		0.384
	2,499		999		0.498
	4,999		2,499		0.722
	9,999		4,999		0.790
	24,999		9,999		1.060
	49,999		24,999		1.487
	99,999		49,999		1.533
	249,999		99,999		1.763
Ψ ≥	250,000				2.473

SOURCE: Meta Systems Inc, *Ibid*.

parameters to fit the above type of equation for each subprocess, allows the planner to use this equation for estimating costs of a new plant as well as of a capacity expansion of a plant.

The parameters of the cost functions are taken from the literature and are either standard engineering estimates* or results of statistical analyses of survey-obtained data.**

Details of the Cost Evaluation Module

The cost evaluation module estimates the costs incurred due to added development within the community and provides an allocation of costs to those groups sharing the project's costs. By varying the cost allocation schemes, the planner is able to generate a range of financial impacts, over time on the community. Thus, the module complements the sewer capacity evaluation module by analyzing the financial impacts of community development. A general logic diagram of the module is presented in Figure 6-3.

Regardless of the cost types j to be estimated, a set of community and development characteristics is required as input:***

a. Projected population/population equivalents of the community for six land uses, for four time periods -- the present (time T) and 10, 25 and 50 years into the future:

    (1) single family -- low density;

    (2) single family -- high density;

---

* K. Shah and G. Reid, "Techniques for Estimating Construction Costs of Waste Treatment Plants," J. Water Pollution Control Federation 42, No. 5, Part I, May, 1970.

** Black and Veatch, "Estimating Costs and Manpower Requirements for Conventional Wastewater-Treatment Facilities," for Environmental Protection Agency, October 1971, Project #17090 DAN.

*** It should be noted that some of the data is deliberately in formats compatible to the sewer capacity evaluation module.

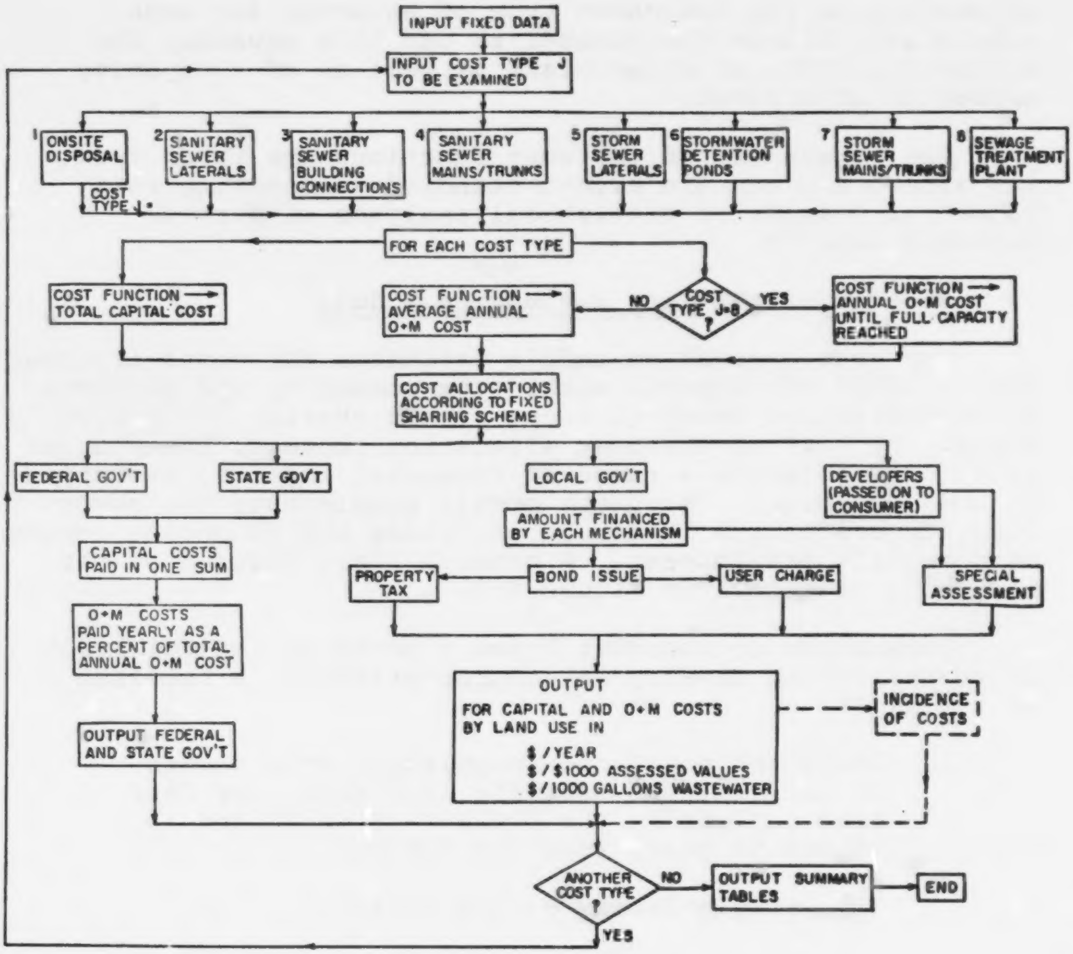

INPUT FIXED DATA
INPUT COST TYPE J TO BE EXAMINED
1 ONSITE DISPOSAL
2 SANITARY SEWER LATERALS
3 SANITARY SEWER BUILDING CONNECTIONS
4 SANITARY SEWER MAINS/TRUNKS
5 STORM SEWER LATERALS
6 STORMWATER DETENTION PONDS
7 STORM SEWER MAINS/TRUNKS
8 SEWAGE TREATMENT PLANT
COST TYPE J =
FOR EACH COST TYPE
COST FUNCTION → TOTAL CAPITAL COST
COST FUNCTION → AVERAGE ANNUAL O+M COST
NO
COST TYPE J=8 ?
YES
COST FUNCTION → ANNUAL O+M COST UNTIL FULL CAPACITY REACHED
COST ALLOCATIONS ACCORDING TO FIXED SHARING SCHEME
FEDERAL GOV'T
STATE GOV'T
LOCAL GOV'T
DEVELOPERS (PASSED ON TO CONSUMER)
AMOUNT FINANCED BY EACH MECHANISM
CAPITAL COSTS PAID IN ONE SUM
PROPERTY TAX
BOND ISSUE
USER CHARGE
SPECIAL ASSESSMENT
O+M COSTS PAID YEARLY AS A PERCENT OF TOTAL ANNUAL O+M COST
OUTPUT FOR CAPITAL AND O+M COSTS BY LAND USE IN $/YEAR $/$1000 ASSESSED VALUES $/1000 GALLONS WASTEWATER
INCIDENCE OF COSTS
OUTPUT FEDERAL AND STATE GOV'T
ANOTHER COST TYPE ?
NO
YES
OUTPUT SUMMARY TABLES
END

Figure 6-3

Logic of Cost Evaluation Module

(3) multi-family;

(4) commercial;

(5) industrial;

(6) open space -- recreational;

b. the expected gallons per capita per day of wastewater generated, by land use;

c. present and projected assessed property values of the community, by land use for the four time periods T, T + 10, T + 25, T + 50;

d. projected assessed property values of the proposed development, by land use for the four time periods T, T + 10, T + 25, T + 50.

e. the numbers and kinds of residential structures to be constructed in the proposed development;

f. expected number of persons per household for the various residential dwellings within the proposed development;

g. interest and discount rates to be used in calculating the cost streams.

In addition to this data, certain development characteristics will be required by the individual cost types j to satisfy the cost functions. The details of such input should be included in a program documentation.

For each cost type j there will be a maximum of up to four groups ℓ sharing the costs:

$\ell = 1$ developer

$\ell = 2$ local government

$\ell = 3$ state government

$\ell = 4$ federal government

Having defined the cost types to be studied, the planner decides on a cost allocation scheme based upon local practices, and state and federal cost sharing programs. Thus, for each cost type j input fectors will be required indicating the percent share of the capital costs $(k=1)$ and the operation and maintenance costs $(k=2)$ to be allocated to each group ℓ.

From this point $\alpha_{jk\ell}$, the share of cost in dollars of cost component k, for cost type j, to be allocated to group ℓ, is calculated. The assumptions made concerning the cost calculations and allocations are:

1. all operation and maintenance costs are in average annual cost except for sewage treatment plants $(j=8)$, for which annual operation and maintenance costs vary in accordance with the capacity utilization of the plant and so are calculated on yearly basis until full capacity is reached.

2. any financing of capital costs by the federal or state governments will be realized in one payment at the beginning of the construction period,

3. any financing of operation and maintenance costs from the federal or state government will be realized as an annual fixed percentage of the costs,

4. within the local government costs may be further broken down by the method in which funds are raised to finance the project:

    a. special assessment -- a one-time charge is assessed against the property owners of the development in dollars per \$1000 assessed value*

    b. bond issue -- the community may decide to float a bond issue in order to finance the cost type. The revenues required to then pay off the bond issue will be raised in two ways:

        (1) property taxes -- the additional tax per \$1000 assessed property values that will be paid by each land use over the bond issue payback period.

        (2) user charge -- given the total amount of revenues to be raised by user charges, the equivalent dollars per capita and

---

* Note: assessed values are obtained from straight line interpolation between time periods.

dollars per 100 gallons wastewater generated are computed by land use.

Required input for the bond issue mechanism includes the payback period, the percentage of the bond issue to be financed by property taxes and user charges, the percentage of each to be paid by the six land uses and, for the capital costs financed with this mechanism, the annual rate of increase in the amount paid back each year.*

Table 6-8 lists the mechanisms which may be employed to finance the individual cost categories.

5. costs borne by the developer will generally be passed on to the consumers within the development in the same fashion as a special assessment by the local government.**

Table 6-9 represents a sample of the output which can be generated by the module. This is for a residential development which requires sanitary and stormwater lateral and interceptor sewers. Capital and operating and maintenance costs for each infrastructure component are listed separately and allocated among different financing methods. The program can also produce more detailed tables indicating the temporal allocation of costs, effects upon property taxes, and the required user charges of each cost type among the various land uses. After examination of the costs the planner may choose to rerun the program with a different local government financing mechanism.

Summary

The fiscal impact module developed in this study provides local and regional planners with an inexpensive and flexible tool for evaluating the economic impacts of

---

* If the annual rate of increase in the amount to be paid back is zero, the annual payback is constant.

** If the housing market is highly competitive, or developers in nearby locations do not have to pay as much, the developer may absorb part of the costs to remain competitive.

Table 6-8

Financing Mechanisms for Different Cost Categories

Cost Categories	On-site disposal		Sanitary sewer laterals		Sanitary sewer building connections		Sanitary sewer trunks/ mains		Storm sewer laterals		Stormwater detention ponds		Storm sewer trunks/ mains		Sewage treatment plant	
Mechanisms	Cap	OM	Cap	OM	Cap	OM	Cap	OM	Cap	OM	Cap	OM	Cap	OM	Cap	OM
Special assessment	x	x	x		x	x	x		x		x		x		x	
Bond Issue																
property tax			x	x			x	x	x	x	x	x	x	x	x	x
user charge			x	x			x	x	x	x	x	x	x	x	x	x

Table 6-9

```
RESIDENTIAL DEVELOPMENT - TEST DATA - JULY 29, 1975

                                              SUMMARY TABLE I
                                              ---------------
                                              TOTAL COSTS (+)
                                              -----------

                                                     LOCAL GOVERNMENT
                                          SPECIAL                        PROPERTY       STATE                FEDERAL
  COST TYPE (++)             DEVELOPER   ASSESSMENT     USER CHARGE         TAX       GOVERNMENT           GOVERNMENT

 SANITARY SEWER LATERALS
    CAPITAL                  303714.81        0.0        60742.97      182228.88      60742.95                  0.0
    O+M                                                   1474.75            0.0        368.69                  0.0

 SANITARY SEWER INTERCEPTORS
    CAPITAL                  278044.31   222435.44            0.0            0.0      55608.85                  0.0
    O+M                                                    162.00         648.00        202.50                  0.0

 STORM SEWER LATERALS
    CAPITAL                   26480.98    13240.49            0.0            0.0      10592.39              2648.10
    O+M                                                       0.0         800.76        228.79               114.39

 STORM SEWER INTERCEPTORS
    CAPITAL                  290222.56        0.0        90694.56      272083.75      72555.63                  0.0
    O+M                                                       0.0         810.00        202.50                  0.0

   (+)  ALL VALUES ARE IN BASE YEAR DOLLARS
        A BLANK ENTRY INDICATES THE GROUP OR MECHANISM IS NOT USED FOR FINANCING THE COST TYPE
        AN ENTRY OF ZERO INDICATES THE GROUP OR MECHANISM WAS NOT CHOOSEN FOR FINANCING THE COST TYPE

  (++)  CAPITAL COSTS ARE IN DOLLARS PER GROUP OR MECHANISM
        O+M COSTS ARE IN DOLLARS PER YEAR PER GROUP OR MECHANISM
```

providing environmental control facilities for new developments. The model can be employed for analyzing the impacts of individual developments or of zoning policies applied to an entire sub-basin. In addition, the impacts of alternative cost allocation schemes can be assessed with this model.

In our introduction to this report, we stressed the importance of considering the interaction between environmental, social, and economic impacts in any land use planning process. Within this framework, a fiscal impact model such as the one developed here performs several important functions:

1. 208 areawide planning calls for an evaluation of the cost effectiveness of alternative physical and land use controls for water quality management. Previously, facility planning under Section 201 of Public Law 92-500 had been concerned primarily with treatment plants and major interceptors. The fiscal impact model makes it possible to include land use control alternatives because it enables planners to consider all relevant control costs, including those of on-lot disposal and local collection costs.

2. Local decision-making on land use takes place in a political context where an overriding concern is often that of fiscal impact and, in particular, residential property taxes. By making it possible to predict at least one class of costs, the fiscal impact model will serve to facilitate local decision-making.

3. The fiscal impact model will enable planners to determine the cost allocations implied by existing pollution control standards and financing policies. Plans and policies can then be designed to alleviate any undesirable distributional impacts which may be revealed. These may involve a change in financing policies or other fiscal measures.

The fiscal impact model which we have developed presently considers only a restricted set of land uses and land characteristics, and employs several cost functions which are in need of considerable refinement and re-evaluation. Nevertheless, we feel that the model, if used properly, will give results which are adequate for many planning purposes. Moreover, we are satisfied that the existing model structure provides an excellent basis for development of a more complete impact model, should that need arise.

Section 7

Land Use Air Pollution Relationships

Introduction

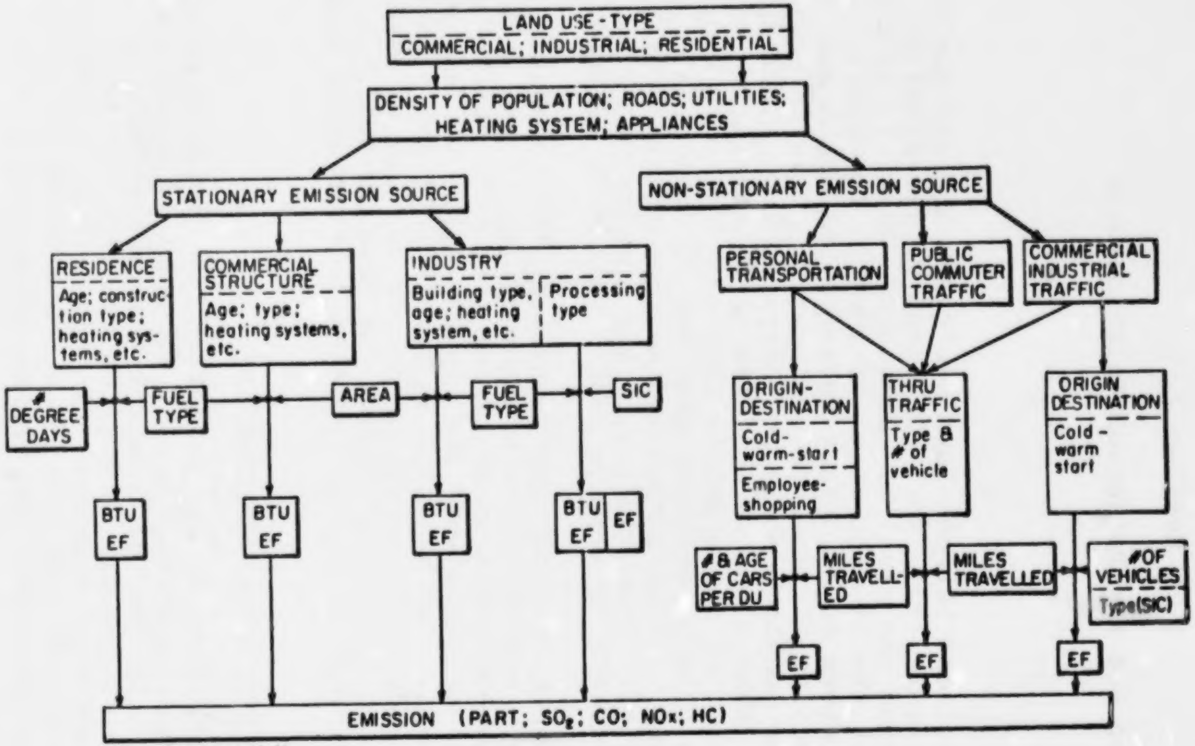
The connections between land use types and air quality are shown in Figure 7-1. The relationships described do not extend beyond the level of emissions. There is little concensus about the present state-of-the-art for models to forecast short-term relationships between emissions and ambient air quality for various pollutants. This is particularly true in modeling non-stationary sources. Therefore, our attempt to show a way of integrating consideration of air, water, and land use planning into one framework would be jeopardized by the potential problems of ambient air quality modeling. If we intend to have congruent efforts with water and air, then short-term air quality modeling rather than modeling of average annual values is desired.

The framework outlined should provide the necessary guidelines for a systematic search through pertinent literature and work-in-progress to determine the state-of-the-art and what models or guidelines are now available for use by land use planners. For example, it should tell the planner where to find industrial emission factors and how to estimate home heating system emissions. We have limited, however, the discussion in this section to stationary sources.

Air Pollution from Stationary Sources

In our evaluation of air pollution, we divide stationary sources into three general types: residential, commercial, and industrial. In the two former types, air pollution results from emissions due to fuel consumption for both space heating and appliance use. In the latter, it results from emissions due to fuel use for space heating and process heating and from emissions due to the processing itself.

The literature on assessing fuel usage for space heating and appliances focuses on four basic methods. The most


LAND USE-TYPE
COMMERCIAL; INDUSTRIAL; RESIDENTIAL
DENSITY OF POPULATION; ROADS; UTILITIES; HEATING SYSTEM; APPLIANCES
STATIONARY EMISSION SOURCE
NON-STATIONARY EMISSION SOURCE
RESIDENCE
Age; construction type; heating systems, etc.
COMMERCIAL STRUCTURE
Age; type; heating systems, etc.
INDUSTRY
Building type, age; heating system, etc.
Processing type
PERSONAL TRANSPORTATION
PUBLIC COMMUTER TRAFFIC
COMMERCIAL INDUSTRIAL TRAFFIC
# DEGREE DAYS
FUEL TYPE
AREA
FUEL TYPE
SIC
ORIGIN-DESTINATION
Cold-warm-start
Employee-shopping
THRU TRAFFIC
Type & # of vehicle
ORIGIN DESTINATION
Cold-warm start
BTU EF
BTU EF
BTU EF
BTU EF
EF
# & AGE OF CARS PER DU
MILES TRAVELL-ED
MILES TRAVELLED
#OF VEHICLES
Type(SIC)
EF
EF
EF
EMISSION (PART; SO2; CO; NOx; HC)

DU = Dwelling Unit
EF = Effluent

Figure 7-1: LAND USE AIR POLLUTANT EMISSION RELATIONSHIP

common is the ASHRAE method.* It calculates the loss from each component of a structure and then, along with certain other factors, adds them to find total hourly heat loss. The next method of calculating heat loss is based on a computer program devised by Hittman Associates. It is called the Time Response Method.** It describes the structure as a thermal system acted upon by internal and external loads. Direct measurement is the third method. Finally, in the case of appliances, utility companies have done saturation surveys to determine how many houses have what types of appliances.

The general approach for converting space heating loads to yearly emissions consists of four basic steps: (1) estimates of hourly heat losses are made; (2) these hourly estimates are converted to yearly values using formulas discussed below; (3) efficiencies in fuel requirements are determined and (4) finally, emission factors such as those developed by the EPA,*** are applied to the fuel figures to determine the resulting emissions.

Emissions from industrial processes are found using EPA emissions factors for the SIC processes. Some literature also exists on fuel usage in manufacturing. These data, along with EPA emission factors for fuel, can be used to give air emissions only for the fuel-using portion of the process.

The three types of stationary sources are discussed below.

Residential Emission

We have computed emissions from a 1,500 square foot house and also from a development of 540 such units by using a variety of literature sources and computing methods. (See values of fuel usage and emissions in Table 7-1.)

---

* American Society of Heating, Refrigerating, and Air Conditioning Engineers, Handbook of Fundamentals, 1972.

** Hittman Associates, Residential Energy Consumption: Verification of the Time-Response Method for Heat-Load Calculation, HUD-HAI, June, 1973.

*** U.S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors, Second Edition, April, 1973 AP-42; relevant emission rates for gas (pounds/10^6 ft.^{3}) and oil (pounds/10^3 gallon) are summarized in Table 7-1.

Table 7-1

Emission Rates*

	Gas[a]	Oil[b]
Particulates	10	10
SO_2	0.6	142S[c]
SO_3		2S[c]
CO	20	5
Hydrocarbons	8	3
NO_2	80	12
HCHO (aldehydes)		2

[a] Emission rate in lbs/10^6 ft.^{3}

[b] Emission rate in lbs/10^6 gal.

[c] S is equal to percent by weight of sulphur in the oil.

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* U.S. Environmental Protection Agency,"Compilation of Air Pollutant Emission Factors, Second Edition, April 1973, AP-42; U.S. Environmental Protection Agency, Supplements #1, 2, and 3 to the above.

The ASHRAE heat loss method is used by fuel companies when calculating the size of unit and amount of fuel needed for a structure. In the ASHRAE method square footage of exposed area is estimated and coefficients of heat transmission are calculated for the different boundaries (masonry walls, windows, etc.). From these values, transmission* heat loss is calculated. From estimates of air exchange and the volume of air in the structure, heat loss from infiltration is computed. The sum of transmission and infiltration heat losses gives the total hourly heat loss. Hourly heat loss is converted to yearly loss by employing the "degree day" method which is based on the lowest outdoor temperature and number of degree days in an area. Then, assuming a fuel use efficiency (e.g., ASHRAE recommends 70 percent for natural gas), the yearly heat loss is converted to its equivalent in fuel quantity. (See summary of method in Table 7-2.)

The New England Fuel Institute (NEFI) makes a slide rule type device called the Heat Cost Calculator.** Yearly fuel usage can be calculated for residences of five different kinds of construction. This gives good results and can be used if the investigator does not wish to calculate transmission coefficients for every type of boundary in the structure or if he only knows the approximate kind of insulation or construction. This calculator is a shortened version of the ASHRAE method combined with the degree day method (see summary of method in Table 7-3). We include in Table 7-4 calculations done with the Heat Cost Calculator for three different kinds of construction.

The Electricity Council Research Center (ECRC) in England has developed a mathematical model of the thermal behavior of buildings.*** It treats the external boundaries as networks of resistances and capacitances, as derived from the thermal properties of the boundaries. The rooms in a

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* By transmission we mean the combined effects of three modes of heat transfer: conduction, convection and radiation.

** New England Fuel Institute, Heat Cost Calculator (Manual Device).

*** P. Basnett, "Modeling the Effects of Weather, Heating and Occupancy on the Thermal Environment Inside Houses," Conference: Mathematical Models for Environmental Problems, Southampton/U.K., September, 1975.

Table 7-2

ASHRAE Method

(Not Room by Room but Over the Whole Structure)

1. To calculate hourly heat loss (BTUH)

   A. Find exterior wall area, floor area, roof area, door area, and window area. If only the square footage of the structure is known, it will be necessary to assume a shape.

   B. Calculate transmission coefficients (u) for each (wall, roof, etc.) by using ASHRAE tables in their handbook. It is necessary to know each kind of construction material used, 1/2" plywood, 2-1/4" fiberglass insulation, single glazed windows, etc.

   C. Assume an outdoor and indoor temperature to get temperature difference across each boundary.

   D. A, B, and C are multiplied together for each component and infiltration is added to the sum.

   E. To get infiltration, cubic feet of the structure must be known along with an infiltration coefficient (ASHRAE tables). This coefficient will vary between residential and commercial, etc. Temperature difference between inside and outside must also be known.

2. To calculate fuel usage

   A. Assume number of degree days.

   B. Assume a correction factor (ASHRAE tables) based on outdoor temperature.

   C. Determine a fuel consumption constant (ASHRAE tables) based on an assumed efficiency of utilization (one could do step 2 on the heat cost calculator if one wished).

3. To calculate emissions: multiply fuel usage by EPA emission factor.

Table 7-3

Heat Cost Calculator Method

1. To calculate Hourly Heat Load
    - A. Know or assume number of cubic feet (square feet x ceiling height) in the structure.
    - B. Assume one of five kinds of construction from not insulated to very well insulated.
    - C. Know outside design temperature.

2. To calculate fuel usage
    - A. Assume number of degree days.
    - B. Assume design temperature difference (difference between indoor and outdoor).
    - C. Assume an efficiency of utilization.

3. To calculate emissions: multiply fuel usage by EPA emission factor for that type of fuel.

Table 7-4

Air Emissions Due to Fuel Use for Residential Heating

			Single Unit[a] A	540 Units A	Single Unit[b] C	540 Units C	Single Unit[c] E	540 Units E	Single Unit[d] Hittman House	540 Units Hittman House	8 units[e] Hittman Town House	540 Units Hittman Town House
Heat Load BTU/year			13×10^7		9.86×10^7		5.78×10^7		8.53×10^7		58×10^7	
Fuel Use[f]		gas ($ft^3 x10^6$)	.179	96.7	.135	72.9	.0789	42.6	.117	63.2	.83	56.0
		oil ($galx10^3$)	1.16	626.0	.880	475.0	.516	279.0	.750	405.0	5.18	350.0
Emissions (lbs.)[g]	particulates	gas	1.79	970.0	1.35	729.0	.79	427.0	1.17	632.0	8.3	560.0
		oil	11.6	6,264.0	8.8	4,752.0	5.16	2,786.0	7 5	4,050.0	51.8	3,500.0
	SO_2	gas	.107	58.0	.081	44.0	.047	25.0	.070	38.0	.498	33.6
		oil	164.7S	88,938S	125S	67,500S	73.3S	39,582S	106.5S	57,510S	735S	49,612S
	SO_3	gas	-	-	-	-	-	-	-	-	-	-
		oil	2.32S	1,253S	1.76S	950S	1.03S	556S	1.5S	810S	10.4S	702S
	CO	gas	3.58	1,933.0	2.7	1,458.0	1.58	853.0	2.35	1,269.0	16.6	1,120.0
		oil	5.8	3,132.0	4.4	2,376.0	2.58	1,393.0	3.75	2,025.0	25.9	1,748.0
	Hydrocarbons	gas	1.43	772.0	1.08	583.0	.63	340.0	.94	508.0	6.64	446.0
		oil	3.48	1,879.0	2.64	1,426.0	1.55	837.0	2.25	1,215.0	15.5	1,046.0
	NO_2	gas	14.3	7,722.0	10.8	5,830.0	6.3	3,400.0	9.4	5,080.0	66.4	4,462.0
		oil	13.9	7,506.0	10.6	5,724.0	6.19	3,343.0	9.0	4,860.0	62.0	4,185.0
	HCHO (aldehydes)	gas	-	-	-	-	-	-	-	-	-	-
		oil	2.32	1,253.0	1.76	950.0	1.03	556.0	1.5S	810.0		

Footnotes: See Table 7-4 (continued) attached.

Footnotes to Table 7-4:

a. House Type A: no insulation, 1500 ft.^{2}, 8 ft. ceiling, 70° indoor, 0° outdoor, 4500 degree days, calculation done with Heat Cost Calculator.

b. House Type C: 2" or more of insulation on walls and ceiling, 1500 ft.^{2}, 8 ft. ceiling, 70° indoor, 0° outdoor, 4500 degree days, calculation done with Heat Cost Calculator.

c. House Type E: 6" insulation on ceiling, 2" or more of insulation on sidewalls, storm sash, 1500 ft.^{2}, 8 ft. ceiling, 70° indoor, 0° outdoor, 4500 degree days, calculation done with Heat Cost Calculator.

d. Hittman House: 5" ceiling insulation, 2-1/4" sidewall insulation, 1500 ft.^{2}, 8 ft. ceiling, 75° indoor, 10° outdoor, 4500 degree days, calculation done using the aggregate form of the ASHRAE method.

e. Hittman Townhouse: 5" ceiling insulation, 2 air spaces in sidewall, each unit 1300 ft.^{2}, 8 ft. ceilings, townhouses in groups of 8 units -- 4 upstairs and 4 downstairs, 75° indoor, 10° outdoor, 4500 degree days, calculation done using the aggregate form of the ASHRAE method.

f. Gas efficiency assumed 70%; oil efficiency assumed 80%.

g. For emission factors, see Table 7-1.

building are linked to each other and to the outside air by these networks. The rooms themselves are treated as individual volumes of air at uniform temperature. The results of the ECRC model have been for the most part good, in that on overcast days calculated consumption has been within 5 percent of measured consumption. The model has not worked so well, though, on sunny days when its values are up to 25 percent away from the measured ones. This deviation has been attributed to the effects of solar radiation, both that which goes directly into the room and that which is stored in the walls, the latter reducing the heat loss during the night. Effort is under way to incorporate these effects into the model.

When ECRC was constructing the model of a wall using the values for conductivity, diffusivity and other factors found in the Institute for Heating and Ventilating Engineers (IHVE) Guide (comparable to ASHRAE), the calculated temperature values were very different from actual temperature measurements made in the wall. ECRC claims this is due to the fact that the IHVE conducts their measurements when the material is quite hot and therefore possesses a lower moisture content. Therefore, values used in the model are slightly different from those in the IHVE Guide. This is interesting in that the loss due to transmission, that part which is calculated using these values, is usually thought to be the most exact part of the calculation.

Before a detailed calculation is presented, another set of heat loss values is compared. Hittman Associates have done a series of residential heating studies for HUD.* As part of their studies, they have developed the Time Response Method, which simulates heat loss in a structure.** Table 7-5 shows values calculated with this method for a 1,646 square foot house. Also included in the series of Hittman reports and Table 7-5 are estimates from fuel executives, servicemen, and measured values. Also listed in Table 7-5 are estimates by Environmental Research and Technology, Inc.

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* Hittman Associates, "Residential Energy Consumption: Single Family Housing," Final Report, March, 1973, HUD-HAI-2; Hittman Associates, "Phase 1 Report, March, 1973, HUD-HAI-1; Hittman Associates, "Evaluation of Heating Loads in Old Residential Structures," January, 1974, HUD-HAI-7.

** Hittman Associates, "Residential Energy Consumption: Verification. 99."

Table 7-5

Yearly Heat Load

ERT High Density	4.7×10^7 BTU	
ERT Low Density	10.4×10^7 BTU	
Hittman use of ASHRAE Method - 1500 sq. ft. house	7.1×10^7 BTU	The same exact house
Fuel Oil Distributor A Hittman 1500 sq. ft. house	7.68×10^7 BTU	
Fuel Oil Distributor B Hittman 1500 sq. ft. house	11.9×10^7 BTU	
Utility A Hittman 1500 sq. ft. house	7.60×10^7 BTU	
Utility B Hittman 1500 sq. ft. house	11.0×10^7 BTU	
Hittman Chart in Phase One Report - Range of Values for 1500 sq. ft. house - (Utility Company's Chart)	$4.1 \times 10^7 \leftrightarrow 7.51 \times 10^7$ BTU	
Hittman Calculation using time response method of heat load for their characteristic house	8.0×10^7 BTU	
Hittman Multi-family Report - 1500 sq. ft. single family house	11.6×10^7 BTU	
Average and range of measured loads in twenty-three 1646 sq. ft. houses in Twin Rivers, New Jersey - Hittman Report	average: 6.9×10^7 BTU range: 4.7×10^7 BTU to 8.8×10^7 BTU	

(ERT) for homes in low density and high density developments.* ERT has not, however, told us how these figures were derived.

The question naturally arises as to what extent the values for heat load or fuel usage for a certain square foot house in a certain area of the country and of a certain type of construction, can be adapted to a house of a different size, in a different area, or of a different kind of construction.

We reproduced a chart from the Hittman report showing ranges of heat load for houses of different sizes (Figure 7-2). The relation is not linear since the addition of a room, for example, includes windows and other components of differing transmission coefficients. Thus it is at best an approximation to multiply a value obtained for a 1,500 square foot house by 4/3 to obtain the load for a 2,000 square foot house. Neither are there easily usable relations between different kinds of construction, short of those obtained through the ASHRAE transmission coefficient tables. Adjustment according to region, however, is an easier matter. The two coefficients used are (1) an adjustment factor for lowest outdoor temperature and (2) the number of degree days. These are purely multiplicative factors.

To illustrate how heat loss computations are made, a sample calculation is presented. In this sample we apply an aggregated form of the ASHRAE-degree day method (see Table 7-2) to a house characteristics of the design employed in the Hittman Associates reports. The home is assumed to be located in Maryland.**

The transmission coefficient, U, is equal to the inverse of the sum of the respective resistances across each layer of the boundary and also those of the air on each side. These resistances are found in ASHRAE tables. U has the dimensions BTUH/ft.^{2}-degree.

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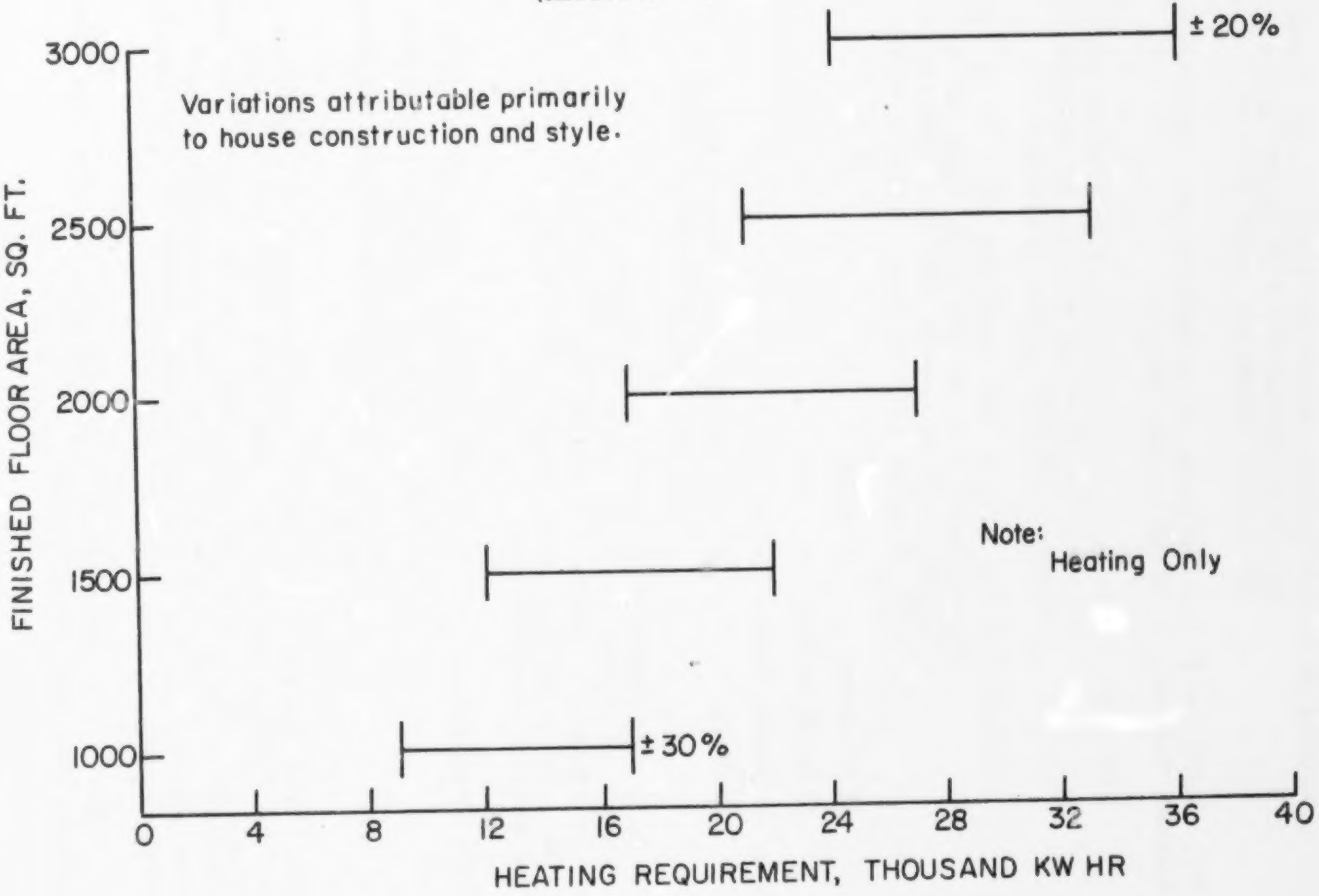
* Environmental Research and Technology, Inc., "Methodology for Determining Emissions from Land Use Planning Data," June, 1972.

** Our aggregated form of the ASHRAE-degree day method applied to another housing structure resulted in a heat loss of about 10 percent less than the one calculated by the room to room method used by ASHRAE. This is an acceptable deviation in the light of all embedded uncertainties.

Figure 7-2

Annual Electrical Heating Use Pattern Versus Floor Area

(Reference 2)



1/Uwalls = .68 (still exterior air) + .81 (wood shiplap) + .62 (1/2" plywood) + .5 (1/2" drywall) + .68 (still interior air) = 3.29 → U = 0.304.

But there is R - 7 Batting (insulation) so, according to the ASHRAE tables, U is adjusted to .1.

1/Uroof: There is an unheated, ventilated attic, but in this aggregated method we assume the roof adjoins the 2nd story ceiling.

1/Uroof and ceiling = .68 (outside air) + .44 (asphalt shingles) + 3.70 for each inch of 5 inch loose fill blown in ceiling insulation and .68 (inside air) = 20.3, so U = 0.05.

U windows = 1.13

U wood doors = .49

U patio doors = 1.

U floor = .2 (this is a very loose approximation based on an ASHRAE example)

If only the area of the house is known, then one must assume a shape in order to find exterior wall area. We assume that it is square. Table 7-6 shows the resulting heat loss in BTUH. To compute yearly heat loss and fuel usage, we apply the Degree-Day Method:

$$\text{Fuel Consumption} = (\text{quantity of fuel used per degree day} \times 1000\ \text{BTUH} \times \left(\frac{\text{BTUH}/1000}{1000}\right) \times (\text{number of}) \ \text{degree days}) \times (\text{temperature correction factor})$$

The first factor is a unit fuel consumption constant given in the ASHRAE Handbook.* BTUH are calculated. The number of degree days (dd) for the area can be found from industry sources or weather bureau data, and the temperature correction factor is found in the ASHRAE Handbook for the lowest temperature in the area (+ 10° in this case).

Thus, the consumption of gas and oil for the same assumptions are as follows:

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* It depends upon utilization efficiency. ASRAE suggests a 70% efficiency for gas, which is what we use -- and an 80% efficiency for oil which we also use.

Table 7-6

Heat Loss Calculation

	U	Exterior Area (sq. ft.)	Temp. Difference Across Boundary	Heat Loss BTUH
Walls	.10	1856	65	12,064
Roof	.05	850	65	2,762
Wood Doors	.49	60	65	1,911
Patio Doors	1.0	40	65	2,600
Windows	1.13	180	65	13,221
Floor	.2	850	25	4,250
Infiltration[1]				15,865
TOTAL				52,673 BTUH

[1] Implies infiltration coefficient of .018 and one air exchange per hour for the house volume of 13,560 ft.^{3}, and a temperature difference of 65° across boundaries.

Gas Consumption (therms) = (.0049/dd/1000 BTUH)
x 52,673/1000 x 1000 BTUH x 4500 dd x 1.167
= 1350 therms.

Oil Consumption (gallons) = (.00304/dd/1000 BTUH)
x 52,673/1000 x 1000 BTUH x 4500 dd x 1.167
= 840 gallons.

The summary of applications of our method and of the heat loss slide rule in Table 7-4 shows that the type of construction will greatly affect fuel usage. The House of Type A uses more than twice as much as the House of Type E. Our aggregated ASHRAE method calculated fuel usage for a house with 5" insulation and no storm windows. Thus, structurally it falls somewhere between Type C and Type E. And our calculation showed that fuel usage also falls in between these two. Moreover, according to our calculations, if the insulation were removed from this house, making its construction comparable to A, then fuel usage would increase approximately 75 percent, a value close to that of House A.

Finally, space heating for residential structures comprises only about 70 percent of total fuel use. The other major fuel using activity is hot water heating, followed in importance by cooking.*

Commercial Emission

Unlike the case for residential structures, there exists no reliable method for calculating heat loss from commercial structures. The heat loss for the same kind of operation in the same type of building can vary by 100 or 200 percent or more. A heating engineer for a local gas company answered us in an interview: "The only thing that's consistent is the inconsistency."** This gas company attempted to relate heat loss from restaurants, for example, to many parameters including size, occupancy, type of establishment and prices on the menu; but the were unsuccessful.

Because of the difficulty of prediction, there exists virtually no literature on heat loss from commercial structures. Almost all of our information was supplied by the aforementioned gas company. In our Table 7-7 we present figures for heat loss for different kinds of commercial establishments which were selected to be representative of their respective categories.

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* Hittman Associates, "Residential Energy Consumption: Single Family Housing.

** Commonwealth Gas Company, Southboro, Massachusetts, June 11, 1975.

We do not have figures for all types of commercial establishments since either they were not on hand at the gas company or because they varied to such an extent that they would be meaningless.

When a heating engineer in the Boston area (5,600 degree days/year) makes a heat loss estimate for a building, to be on the safe side he usually begins with a figure like 50 BTU/ft.^{2}. This assumes about 4-inch wall insulation and 6-inch ceiling insulation. The actual loss is more like 35 BTU/ft.^{2}. This will vary greatly, of course. The gas company's building is new and well-designed so heat loss is about 20 BTU/ft.^{2}. An old building will have a heat loss greater than 50 BTU/ft.^{2}. But as we have already noted, this will vary to a great extent according not only to the type of establishment but to which particular establishment one is studying.

It should be noted that one of the differences between commercial or industrial and residential is that the first two have specified hours of operation during which the temperature is kept higher than during the off-hours. The American Gas Association, therefore, recommends the following method of finding an average indoor temperature and of proceeding to an annual fuel requirement:

Degree hrs./week = temperature x (hrs. per day) x (days/week)

(Degree hrs./week)/(168 hrs./week) = average temperature indoor

(BTU/hour heat loss) x 24/(Design temperature difference) = BTU/Degree Day

(BTU loss per Degree day) x (Degree Day/season)/heating efficiency = fuel required per season.

Thus, if on weekdays a store is open for ten hours during which the temperature is kept at 70°, closed for 14 hours during which the temperature is kept at 60°, and then on weekends closed for 24 hours during which the temperature is kept at 50° then,

Table 7-7

Fuel Usage and Emissions for Selected Commercial Establishments[a]

		Supermarket	Discount Store	Warehouse	Warehouse	Car Dealer	Distributing Warehouse	Large Office	Cinema
area ($ft^2 x 10^3$)		30.	55.04	41.6	54.4	16.72	400.0	201.0	not available
volume ($ft^3 x 10^3$)		360.	770.6	832.0	1,360.0	200.6	18,400.0	4,828.0	not available
1973-1974									
Measured Gas ($ft^3 x 10^6$)		2.92	1.63	3.35	7.6	2.13	32.26	13.54	4.46
Oil (gal $x 10^3$)		18.96	10.56	21.77	49.40	13.82	209.7	87.99	29.02
Emissions (lbs.)[b]									
particulates	gas	29.16	16.25	33.49	76.00	21.27	322.6	135.4	44.64
	oil	189.6	105.6	217.7	494.0	138.2	2,097.	879.9	290.2
SO_2	gas	1.75	.98	2.01	4.56	1.28	19.36	8.12	2.68
	oil	2692S	1500S	3091S	7015S	1962S	29,777S	12,494S	4121S
SO_3	gas	-	-	-	-	-	-	-	-
	oil	37.9S	21.12S	43.54S	98.8S	27.64S	419.4S	175.98S	58.04S
CO	gas	58.32	32.50	66.98	152.0	42.54	645.2	270.8	89.28
	oil	94.8	52.8	108.4	247.0	69.1	1048.5	440.	145.1
NO_2	gas	233.3	130.	268.	608.	170.	2581	1,083.	357.
	oil	227.5	126.7	261.2	592.8	165.8	2516	1,056.	348.2
HCHO aldehydes	gas	-	-	-	-	-	-	-	-
	oil	37.92	21.12	43.54	98.8	27.64	419.4	175.98	58.04
Hydrocarbons	gas	23.33	13.0	26.8	60.8	17.0	258.1	108.3	35.7
	oil	56.88	31.68	65.31	148.2	41.46	629.1	264.0	87.06

a. Gas use measured by Commonwealth Gas; to get oil use we first multiplied gas value by .7 (thus assuming 70% gas efficiency). This gave us heat load. We divided this by .8 (thus assuming 80% oil efficiency) thereby getting oil use.

b. For emission factors, see Table 7-1.

$$\begin{array}{rcl} 70 \times 10 \times 5 & = & 3{,}500 \\ 60 \times 14 \times 5 & = & 4{,}200 \\ 50 \times 24 \times 2 & = & \underline{2{,}400} \\ & & 10{,}100 \text{ degree hrs./week} \end{array}$$

$$\frac{10{,}100}{168} = 60^\circ \text{ average indoor temperature.}$$

Industrial Emission

Air emissions due to industrial processing can be found by referring directly to EPA's compilation of emission factors.

Air emissions due to fuel use for space heating is much more difficult, however. Environmental Research and Technology, Inc. (ERT) has done a study in which they present figures for different industries; but the variances are so huge that ERT expressed warnings in their report with respect to the unreliability of the figures.*

Heat loads for industrial establishments cannot be calculated on the basis of physical characteristics of the building since machinery produces large heat gains. There is therefore great interaction between process heat and space heat. This is obvious in the case of a steel mill. And in Hartford, for instance, an office building is supposedly being heated with the heat given off by the computers within the building. Therefore, when machinery is involved, it is futile to make estimates which disregard the large heat gain. Moreover, the myriad number of ways of ordering activities within a manufacturing establishment make estimation even more difficult.

Thus, the method used to calculate heat loads for residential structures is for the most part not applicable to industrial structures unless the large internal heat gains are also taken into account.

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* Environmental Research and Technology, Inc., Air Quality for Urban and Industrial Planning, March, 1974; U.S. Environmental Protection Agency, "A Guide for Considering Air Quality in Urban Planning," March, 1974.

Summary

In order to get a rough idea of the importance of emissions due to space heating in comparison to total industrial emissions, we give values of emissions for several paper production plants, a group of open hearth furnaces, an electric arc furnace, and a coal-burning power plant in Table 7-8. As can be seen, emissions due to space heating for developments such as we are considering seldom come close to those from other activities.

This is not to say that emissions due to space heating should not be taken into account. Space heating produces 8 million tons of the nation's 133 million tons of air pollution produced per year.* Thus while small, it is not inconsequential. Moreover, local effects of space heating may be significant in particular areas.

On the level at which we are speaking then, small differences due to different methods of estimation do not make much cumulative difference. In the case of residential heating, the planner can go through the simple ASHRAE method. In the case of commercial heating, he can make use of the approximate values we give in the tables, a rough factor such as 35 BTUH/ft.^{2}, the ASHRAE method, or a combination of all three. Finally, in the case of industrial sources, EPA emissions estimates, scaled down by the analyst for internal heat gain, can provide the basis for emissions estimates.

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* Edmund K. Faltermeyer, "We Can Afford Clean Air," in Pollution: The Effluence of Affluence, Frank J. Taylor, Philip G. Kettle, and Robert G. Putnam, Methuen, 1971.

Table 7-8

Emissions from Selected Activities

1. Iron and Steel[a]

	Particulates (lbs/day)
13 open hearth furnaces (175 ton is the rated capacity of each)	26,800 (Best available technology -- 5,100)
Two electric arc furnaces (50 ton is the rated capacity of each)	5,250 (Best available technology -- 600)

2. Paper and Pulp[b]

	Particulates (lbs/day)	TRS* (lbs/day)
Number of Selected Plants	1,000	57.7
	4,000	240.
	--	2,750 (SO_2 only)
	6,136	7,000 - 9,000
	7,625	2,500 - 3,000

3. Coal Fired Power Plant[a]

	Particulates (lbs/day)
300,000 kw with good dust collector	11,000
300,000 kw with fair dust collector	40,000

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* TRS = total residual sulphur (Hydrogen Sulfide, Methyl Mercaptan, Dimethyl Sulfide, Dimethyl Disulfide).

[a] Schueneman, J., _et al._, _Air Pollution Aspects of the Iron and Steel Industry_, U.S. Department of Health, Education, and Welfare, 1963.

[b] Council on Economic Priorities, _Paper Profits_, MIT Press 1972.

Appendix A

Data Collection for STORM and SWMM

The Mill River Drainage Basin*

The portion of the Mill River Basin investigated in our study extends from Whitney Lake Dam to the headwaters. The drainage basin above the lower limits of this study area is 37.7 square miles and is of triangular shape, about 13.5 miles long and about 5.5 miles wide at the upper end. Elevations range from 880 feet (MSL) on top of Mt. Sanford to 36.3 feet (MSL) at Whitney Lake Dam Spillway. The Mill River flows in a southerly direction adjacent to Route 10 from the center of Cheshire in the vicinity of Route 70 to New Haven Harbor and Long Island Sound. The average slope is 20 feet per mile from the headwaters in Cheshire to the Hamden town line and 9.4 feet per mile from the Cheshire-Hamden town line to Whitney Lake Dam.

The largest tributary to the Mill River is Willow Brook with a drainage area of about 12.7 square miles. It joins the river in Hamden near the Cheshire-Hamden town line. Other contributors to the flow on the river are Butterworth Brook, Jepp Brook, Eatons Brook and Shepard Brook.

There is one major dam in the Mill River System: Whitney Lake Dam. The dam, constructed in 1860-61, was modified in 1916 and now has a spillway crest length of approximately 250 feet. A flow rating curve of the dam was drawn by Malcolm Perne as part of a study entitled "Report on the Effects of Flood Flows on the Lake Whitney Dam", done for the New Haven Water Company in May 1956. The curve is

$$Q = CLH^{1.5} \qquad \text{(A-1)}$$

with $C = 3.3$, reflecting a Broad Crested weir;

$L = 250$ feet, the effective length of the weir; and

H = head on the weir (water level).**

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* Most of the following information is drawn from a floodplain study made by the Corp of Engineers: Floodplain Information, Mill River, Hamden, Connecticut, Prepared for the town of Hamden by Department of the Army, New England Division, Corps of Engineers, Waltham, Massachusetts, March 1968.

** Above a head of one foot a correction factor was applied due to submergence of the side channel portion of the spillway.

Since the spillway crest is long, the spillway is capable of passing high flows at relatively low heads. Lake Whitney has a useable storage of 258 million gallons.*

Flow records on the Mill River are sparse; no official gauging stations exist. The only recording has been done by the New Haven Water Company. Daily levels of Lake Whitney at the company's water intake have been monitored since 1897. During the 40-year period from 1918 to 1957 the average flow at the dam was 42 mgd. Thus, the average detention time is about 6.1 days. The minimal annual average flow for the above period was 26 mgd in 1930 (i.e., about 8.2 days of detention in the lake) and maximal was 77.2 mgd in 1953 (i.e., about 3.3 days of detention). No travel time estimation has been performed for the Mill River. The travel time from the Hamden-Cheshire town line to Waite Street (the upper end of Lake Whitney) is about 12 hours for a flow velocity of 1 foot per second. Some profiles of the Mill River are kept in the files of the U.S. Army Corps of Engineers originating from their floodplain study.** They were used for developing the data necessary for the modeling efforts.

The drainage was divided into sub-basins. Natural drainage patterns determined the selection of the following 11 sub-basins (see Figure A-1):

Lake Whitney (West)
Lake Whitney (East)
Shepard Brook
Centerville and Hamden
Central Mill
Eaton Brook
Northern Country Club
North-Eastern Mill (Butterworth)
Willow Brook -- Hickory Jeep
Willow Brook North (including parts of Cheshire)
Mill River (Cheshire)

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* S. Jacobson, E.L. McLeman and R.E. Speece, "Estimating Reservoir Yields on a Digital Computer", J. American Waterworks Association, January 1959, pp. 51-54.

** U.S. Army Corps of Engineers, op. cit.

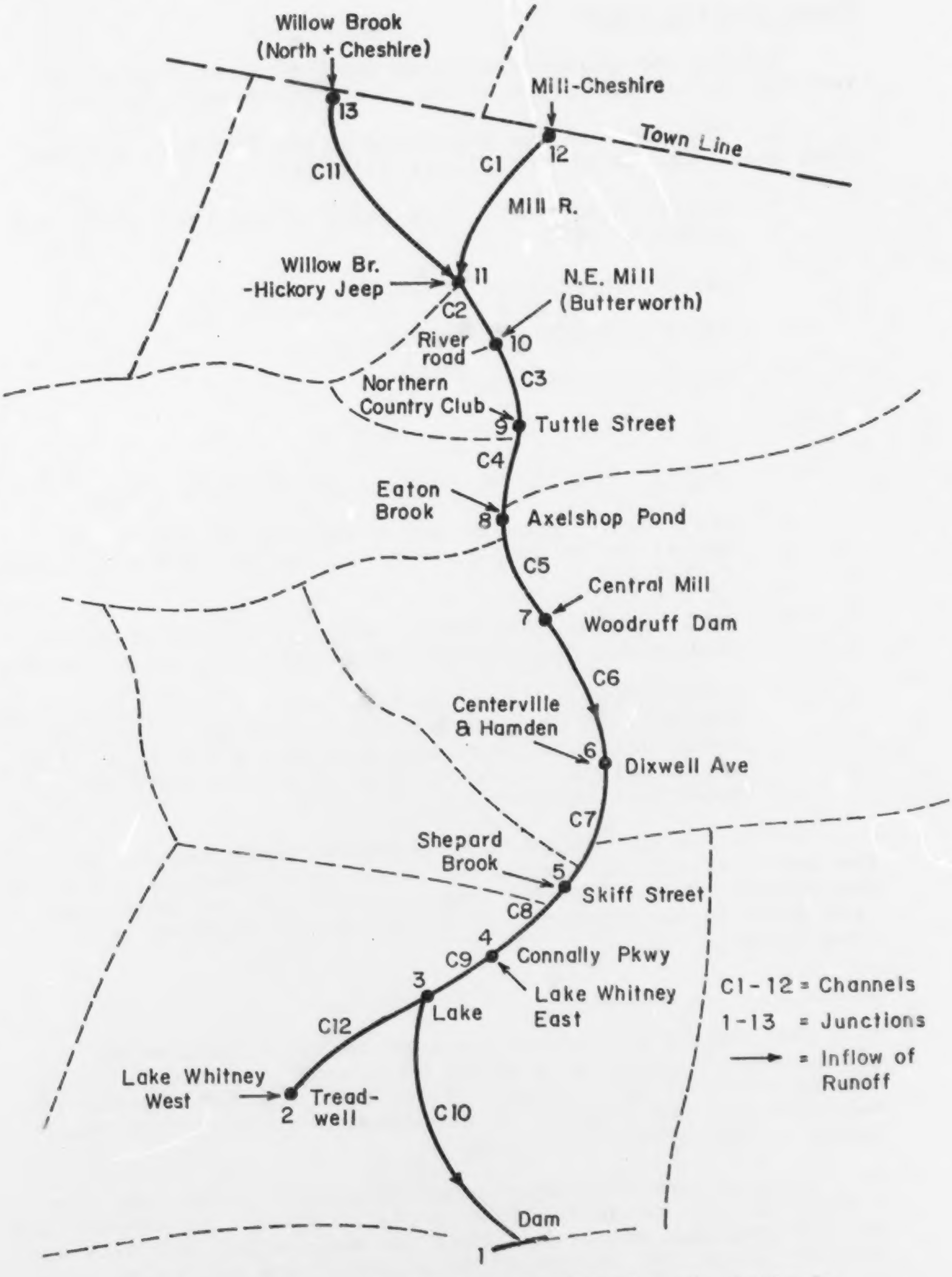
Willow Brook
(North + Cheshire)
13
Mill-Cheshire
12
Town Line
C11
C1
Mill R.
Willow Br.
-Hickory Jeep
11
N.E. Mill
(Butterworth)
C2
River
road
10
C3
Northern
Country Club
9
Tuttle Street
C4
Eaton
Brook
8
Axelshop Pond
C5
Central Mill
7
Woodruff Dam
C6
Centerville
& Hamden
6
Dixwell Ave
C7
Shepard
Brook
5
Skiff Street
C8
4
Connally Pkwy
C9
3
Lake Whitney
East
Lake
C12
Lake Whitney
West
2
Tread-
well
C10
Dam
1
C1-12 = Channels
1-13 = Junctions
= Inflow of
Runoff

Figure A-1: Conceptualization of Mill River for Analysis

Water Quality Data*

During the search for water quality data sources of varying reliability, precision, and extent were found:

1. The data of the New Haven Water Company, derived from grab samples at the filter intakes:

- daily coliform (5 days/week) since 1966, data are given as MPN)
- daily temperature of intake water
- daily outside temperature
- daily precipitation
- daily intake of water (mg)

  (note: all the above data exist since 1923

- daily data of color and turbidity (5 days/week) (note: these data must be extracted from unofficial files)
- published monthly data: average values of color, turbidity, and precipitation from the daily records
- quarter-yearly data on odor, color, chlorides, free ammonia, albuminoid ammonia, nitrites, nitrates, total hardness, conductivity, pH, alkalinity, iron, total solids, fixed solids, fluoride, calcium, magnesium, copper and sodium.**

2. A few grab samples of physical and chemical data of raw water at the filter intake point were taken by the State Department of Health; they are available on magnetic tape from 1966 to the present. Six samples of interest were identified.

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* Our report is limited to surface water because no groundwater quality data could be found. Dr. D.E. Hill of the Connecticut Agricultural Experiment Station (New Haven) believes that no samples of groundwater quality have been taken on any systematic basis.

** Some of the data exist only in recent years; but turbidity, color, chlorine (from NaCl), nitrogen as ammonia and as nitrites and nitrates, total hardness and alkalinity are sampled since the twenties; total and fixed solids as well as iron were added in the thirties, while oxygen consumed (COD) was dropped.

3. For one year (July 1955 to June 1956), weekly samples of MPN, nitrite nitrogen, nitrate nitrogen, chlorides, soluble orthophosphates (PO_4), pH, alkalinity ($CaCO_3$) and acidity (as CO_2) are available for a network of six stations (3 at Lake Whitney, 3 at the Mill River). Some sampling stations are located at tributaries of the Mill River, such as Shepard Brook. Most of the data have to be read from graphs in the official publication.*

4. For the period of March to November 1973 (except August), the Quinnipiac College took monthly samples at four locations in Clarks Pond and at two close points upstream and one downstream of the pond.** Various biological as well as physical and chemical indicators were sampled from a rowboat within the pond: water temperature; DO; free CO_2; pH; H_2S; NO_3; NO_2; NH_3; organic N; PO_4; metaphosphate; silica; color; turbidity; SO_4; total hardness; Cl; Fe; BOD; oxygen demand index; conductivity.

5. Some samples were taken by the Southern Connecticut State College:*** total solids, dissolved oxygen, and turbidity were sampled five times during a three-week period in spring and five times during a three-week period in summer over a period of three years; scattered measurements of chlorides, nitrates, and phosphates were taken. Measurements were made at Clark's Pond, Sleeping Giant, and Dixwell Bridge. More complete bi-weekly measurements at six points on the river were taken since August, 1974; the data were promised but have never been made available.

Without discussing details of the available data the following points should be made with regard to the desirable calibration of the water quality model:

- there exist long time series at the intake point for all the major constituents except for soluble ortho-phosphates (PO_4); but they are mainly quarter-yearly data except for daily coliform, temperature, color and turbidity data;

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* S. Jacobson and E. L. MacLeman, "Lake Whitney Sanitary Conditions in Relation to Certain Laboratory Examinations," J. NEWWA, 1959, pp. 62-88.

** The purpose of the study was to find out the reason for incomplete decomposition of plant life (including poison ivy) in the pond: Collen G. Becker, *et al.*, "A Limnological Study of Benthic Decomposition in Clark's Pond, Hamden, Conn.," Senior Research Paper, Dept. of Biology, Quinnipiac College, 1973.

*** Dr. Dwight Smith is the faculty member responsible for this research.

- there exist almost no cross-sectional data for total solids;
- there exist almost no BOD-DO measurements;
- there exist no reaction rates of non-conservative constitutents in the water body;
- there exist very few cross-sectional data, compared to the number of time-series data at the intake point to the filters; the few available cross-sectional data do not contain any flow measurements;
- missing data in the series of daily data had to be estimated because no water quality samples are taken on holidays.* Sampling is also not conducted on weekends, so it was decided to work with a five-day week.

Climatological Data

The New Haven Water Company and the Mt. Carmel Weather Station report daily temperature and precipitation data. The former are available from the company's records, while the latter can be received from the U. S. Commerce Department's climatological reports. The Bridgeport airport weather station is the nearest station which has recorded hourly precipitation data up to date as needed for the runoff model (see Table A-1 for analysis of 1974 precipitation record). The direct transfer of information from this station to the Hamden area might result in incorrect precipitation input. But this problem is common for almost every study so that some guiding assumptions have to be made. Otherwise the application of the models would not be justified at all.

Drainage in the Hamden Area

The following brief section describes storm water drainage characteristics prevailing in the subbasins in the

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* A linear smoothing function was used to compute the missing data; i.e. the average of the preceding and of the succeeding measurement were taken. See also: R.E. Wyzga, "Note on a Method to Estimate Missing Air Pollution Data", J. Air Pollution Control Association, Vol. 23, No. 3, March 1973, pp. 207-208.

Table A-1

Number of Days per Precipitation-free Interval 1974: Bridgeport Airport

Interval w/o Precipitation (days)	No. of Days w/o Precipitation
1/2	76
1	12
1 1/2	8
2	6
3	20
4	12
5	9
6	10
7	3
8	4
9	1
10	3
11	1
>15	2

Hamden area. The sanitary sewer system is connected to the New Haven System. No combined sewers exist which could overflow in the Mill River. Therefore the sanitary sewer system is not further discussed.

Lake Whitney West. This area has storm sewers. The waters from the area to the south of the western fork of the river run off across Putnam Avenue to an outfall on the fork, and the stormwaters from the west of the western fork discharge to three or four outfalls. The fork divides the runoff, with half flowing to outfalls on the western fork and half flowing into Lake Whitney itself. There is a drainage problem on Augur Street.

Lake Whitney East. This area is storm sewered for the most part, with outfalls at many points to the river. There is a portion of residential area, however, that is not storm sewered. Some of the runoff from the central portion of this sub-basin flows into a brook and then to the river.

Shepard Brook. For the most part this area is not storm sewered. Most of the runoff flows into Shepard Brook and then into the river, though some finds its way into ditches. The waters from the storm sewers on Shepard Avenue flow into the Brook at several points.

Centerville (Hamden). This is for the most part storm sewered with outfalls at various points on the river. There are two drainage problems: one where Pardee Brook (which also carries some of the area's runoff) runs into an apartment complex, and another on Forest Street off Whitney Avenue.

Central Mill. Some of the runoff from this area runs into a brook and then into the river. Some also runs over Mt. Carmel Avenue and then to the river.

Eaton Brook. Much of this is not storm sewered. The part which runs partly down Shepard Avenue into Shepard Brook and partly over West Todds Road into the river. Runoff also flows into Eaton Brook and then to the river.

Northeast Mill. This area is not storm sewered. Some of the runoff flows into a small brook and then to the river.

Northern Country Club and Willow Brook. There exist very few storm sewers here. The existing ones lead over Still Hill into River Road and then down Whitney Avenue into an outfall on the river. Some of the runoff flows into Willow Brook, while some flows into a ditch.

Data on Soil and Slope Characteristics

Maps from the Soil Conservation Service, U.S. Department of Agriculture, showing soil and slopes of our sub-basins and a booklet,* prepared by the Connecticut Soil Conservation Service, were available. The preparation of data for all sub-basins to be used in the universal soil loss equation took considerable time.

1. Cheshire silt loam, a well-drained soil; hydrologic** group B; and K-factor = .43
2. Penwood loamy sand, an excessively well-drained soil; hydrologic group A; K-factor = .17
3. Cheshire fine sandy loam, well-drained; hydrologic group A; K-factor = .17
4. Wethersfield loam, well-drained but having a shallow fragipan which restricts internal drainage; hydrologic group C; K-factor = .43, B Horizon = .17
5. Watchaug fine sandy loam, moderately well-drained; hydrologic group B; K-factor = .43
6. Manchester gravely sandy loam; excessively drained; hydrologic group B; K-factor = .43
7. Holyoke rocky silt loam (also 94L and 94M, which are, respectively, very rocky and extremely rocky); a very rocky poorly drained soil; hydrologic group D; K-factor = .43
8. Urban land
9. Branford silt loam, well-drained; hydrologic group B; K-factor; B Horizon = .64; C Horizon = .17.

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* U. S. Dept. of Agriculture, Soil Conservation Service, "Special Soils Report: New Haven County, Connecticut, Soil Interpretations for Urban Uses", 1972 and "Know Your Land, Natural Soil Groups for Connecticut", Cooperative Extension Service, Storrs/Conn., 1972.

** The hydrologic groups A to D reflect the drainage characteristics of the soils; a soil of group A has the best drainage. The K-factor describes the erodibility of a soil.

The following section describes the soils found in the different sub-basins.

Lake Whitney West. This sub-basin consists primarily of urban land and Penwood. Some Manchester is also found along with smaller quantities of Cheshire and Wethersfield. The land is for the most part flat.

Lake Whitney East. This consists of mostly urban with a large amount of Branford. Some Manchester is also found along the river. The land is fairly flat.

Centerville. In the southern part there is a good deal of Branford, while in the northern part, some very rocky Holyoke occurs which is moderately to steeply sloped. There is a strip of Branford which stretches up the length of the sub-basin as well. Other than that, there is mostly Cheshire, both silt and fine-sandy.

Central Mill. This area consists mostly of lightly to moderately sloped Cheshire and moderately to heavily sloped Holyoke. The Holyoke is especially predominant in the northern part.

Shepard Brook. This area consists mostly of moderately to heavily sloped Cheshire and heavily sloped Holyoke. It becomes flatter in the southern part.

Eaton Brook. This portion consists of a lot of Cheshire, but some Branford, Holyoke, Wethersfield and Watchaug are also found. The slopes vary.

Northeastern Mill. This section consists mostly of very rocky to extremely rocky Holyoke, with steep slopes. A mix of other soils including Cheshire, Manchester and Branford is also present.

Willow Brook. A lot of Cheshire is found here, lightly to moderately sloping. A mix of other soils is also found.

Northern Country Club. This is mostly Holyoke, with some Cheshire and Manchester.

The rainfall factor "R" for the region is assumed to be "150" according to the "iso-erodent" maps.*

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* U.S. Department of Agriculture, Agriculture Research Service, Rainfall-Erosion Losses from Cropland East of Rocky Mountains, U.S. Dept. of Agriculture, Agricultural Handbook No. 282, 1965.

Land Use Data

Present Availability

The land use data for the Mill River Basin is available from five sources for the town of Hamden, the core of the basin, and available only for the most recent period for North Haven and Cheshire, the eastern and northern edges of the basin. The data which is available is of high quality and reasonably consistent, permitting the flexibility of creating, through interpolation and research in town records, continuous land use data for that portion of the basin within Hamden. It should be noted, however, that the quality of data available for Hamden is not representative of that generally available in communities within the U.S. The implications of this will be discussed.

Hamden's first land use survey was undertaken in 1941.* The second land use survey, and the first available to Meta Systems, was done by Technical Planning Associates of North Haven in 1948-49, "A Pilot Study for a Town Plan." The results of this study are presented on an exceedingly large scale map presented in the report. The study reported land use by 13 categories, only three of which would be comparable to more recent land use studies showing compact residential, commercial, industrial and rural uses. While this map is difficult to use for detail, it is a useful benchmark from which to begin a study of those areas which were densely developed in the immediate post-war period. Furthermore, the street pattern on that map gives a clear indication of the built-up areas. This map combined with analysis of subdivision permits from the same period could be used as an accurate starting point of a study of the residential, industrial and commercial land uses for the town. To extract agricultural land use is considerably more difficult both in the early and later studies because the definition of types of land uses is far less clear. It is generally not possible to tell when a piece of land was taken out of active production and entered a speculative period prior to its development for residential purposes. Further, many of the farms ceased to be productive even though they were not immediately broken up for development. It is obvious that the available data on this sector are limited for non-point source/water quality considerations.

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* We report this part in detail because it gives the potential user an idea of the efforts needed to utilize even a relatively uncomplicated model such as STORM.

In 1954-55 Maurice E.H. Rotival and Associates prepared A Short Approach Plan for Hamden. This report contained an existing land use map, again of only moderate detail and scale. Residential single family is the only family classification employed, along with community, industrial, institutional and several classifications for utilities. As with the 1948 survey the detail contained is not sufficient for purposes of a good intertemporal land use analysis but may offer a second view of community settlement patterns (through the road system) with which to follow the pattern of development occurring in Hamden.

In 1963 Goodkind and O'Dea carried out a comprehensive land use study of the town of Hamden. This study has become the basis for all subsequent planning and zoning in the community. At the time of the study the town also had a set of aerial photographs taken by the Sanborn company; these are available in the Town Hall.

The land use material presented in the Goodkin and O'Dea report is on 1" to 200' scale maps which have become the basic planning maps for the town of Hamden. The accompanying report contains detailed land use information on six classifications of residential land use, two major classifications of industries, utilities, institutional and other land uses (which includes agricultural uses).

In 1974 a land use map of Hamden was prepared by the staff of the University of Southern Connecticut. This land use effort parallels closely that of Goodkind and O'Dea in 1963, but at a scale of roughly 1:2,000. There is only one copy of this map; it is available in the town planning office of Hamden.

Land use information for the remainder of the basin is far less complete than that for Hamden. Both the Towns of Cheshire and North Haven are without major land use maps of any point in time. North Haven maintains a file of information concerning past zoning in the community. Cheshire maintains only a current zoning map.

One additional and potentially significant land use map for the region exists at the USGS headquarters in Reston, Virginia and at the Department of Geography at Dartmouth, N.H. This map of the New Haven metropolitan area was developed as a prototype mapping system by Robert Simpson of Dartmouth and the USGS. The map is at a large scale, 1:100,000, and covers an area of roughly 16 by 20 miles. It has been developed from high altitude photographs and verified from low altitude. The scale of the map makes it less useful for this analysis, and it is for only one point in time.

Given these considerations, however, the work is of considerable assistance in defining present land uses in areas peripheral to the basin. The system employed recognizes two classifications of housing -- single family and multiple family or mixed family, industrial, commercial, transport and utilities, institutional, recreational, agricultural, forest and vacant land.

In summary, the land use information available for the Mill River basin is considerably better than that for most communities within the United States. The data for Hamden is of relatively consistent quality over a twenty year period and of excellent quality over the past ten years. Effort is required, however, to interpolate between the views provided by the various types of data. The availability of a large scale recent land use map for the entire New Haven Metropolitan region allows for complete information on current land use within the basin in the Communities of North Haven and Cheshire where no town level information is available. Use of the USGS map is unfortunately limited because at present only two prototypes of these maps exist.

Collection of Land Use Data

There were two major considerations in our collection and storage of land use information: first, the need for a system sufficiently general to be applicable to a large number of sites where similar analyses would be undertaken; and, second, development of a structure for collection and storage which mirrors the needs of the analytical tool being developed. The smaller the unit for data collection, the more flexibility will be available to the researcher for aggregating data to a number of political and physical configurations. Efforts have been made to develop general models using disaggregated data; the National Science Foundation-sponsored research on land use and environmental modeling at the Harvard Graduate School of Design is one such case.* The question of the appropriate size of basic grid cells is not an easy one to answer. There are as many answers as there are problems which require a spatial framework for analysis. Clearly the choice of a grid size for land use work must be determined by the specific analysis being undertaken, by the level and quality of data available and by the cost effectiveness of finer and finer levels of detail. In many planning environments the level of detail required of a data system such as that developed by the group at Harvard Graduate School of Design is not available and cost constraints prevent the collection of such data.

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* See: The Interaction between Urbanization and Land: Quality and Quantity in Environmental Planning and Design, Landscape Architecture Research Office, Graduate School of Design, Harvard University, Cambridge/Mass. Progress report for years one to three, October, 1974. (NSF RANN grant No. GI-32603) See also: Tabors, Richard and Michael Shapiro "Land Values and Public Investment in Urban Fringe Areas: A case study of Clay, York". Environmental Systems Program. Harvard University, Cambridge/Mass., Working Paper, January 1975.

The geographic grid structure which we have applied in the Mill River Basin is, we believe, a sensible compromise which retains the advantages of a grid structure for storage and retrieval of information and aggregation to various configurations, but also retains a level of simplicity both in collection and storage that can be implemented within a planning office. The unit of data collection for the study was fixed at 1/4 square mile or 160 acres. This selection was based on several general considerations. First a lower bound on the grid size was set by the quality of data available. Given the data base described above, a substantially smaller grid, such as the one hectare size employed by the study at Harvard Graduate School of Design, was not warranted. Moreover, this conclusion was reinforced by our *a priori* beliefs about the sensitivity of the runoff model. It was felt that, given the hydrologic characteristics of the region and the nature of the model it would not be possible to determine the impact of land use changes in individual cells as small as 2.5 or even 20 acres. At the upper limit, the grid size was constrained by our selection of sub-basins as the fundamental unit of the impact analysis (see below). Since these basins were as small as two square miles, a grid cell much larger than 1/4 square mile, say 1/2 square mile, would have provided little more information than analysis on the sub-basin level alone. In addition, there would have been excessive difficulties in trying to reconcile grid cells which overlapped drainage basins.

Given these limitations, there still existed a substantial range of potential grid sizes, from roughly 20 to 320 acres. The selection of the 160 acre grid was an arbitrary but, we feel, reasonable choice from among these remaining possibilities. In addition, a number of previous studies of infrastructure costs (see Section 6) had employed a 160 acre grid. Thus the use of this size permitted us to compare the results of our cost analysis with other results.

One of the considerations in the organization of a data system for the Mill River Basin was the structure of information required by the STORM model; STORM is designed to work on basins of less than 10 square miles.* Based on the natural drainage conditions, the Mill River Basin was divided into a series of sub-basins, each in the range of two to nine square miles.* In addition to this criterion, the intertemporal development patterns of the community became a major criterion for this dividing pattern. Thus, in the entire Mill River Basin we have defined three sub-basins that comprise most of the older portions of the town of Hamden, two that cover the new development areas of Hamden, and the remainder which cover the less developed regions of the three towns.

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* See Section 5.

Each of the sub-basins has a relatively different path of development in both time and space. For instance, the Shepard Brook area has seen development in the southern portion since the nineteen-fifties. The development has proceeded north in the basin constrained only by the availibility of land for development and the existence of a large industrial park in the center of the sub-basin. The zoning of the industrial area prevented the use of that land for any other purpose. Because the industrial development was slow, the center of the basin has remained relatively open until quite recently. The Eaton Brook, the sub-basin to the north of Shepard Brook, has yet to see any major development. Only in the last five years has there been any construction activity and that only of single family housing on relatively large and isolated lots. The character of each of the 11 sub-basin areas is sufficiently different to allow for comparison on temporal and spatial growth within the total Mill River Basin.

A significant aspect of our analysis of the methods applied and of the use of the STORM model requires the analysis of the spatial sensitivity of the model. To accomplish this we have chosen one sub-basin, that of the Shepard Brook, for a study in such detail sufficient to attempt to identify the impact of concentrated development activities as small as 160 acres, the size of a moderate housing development. Our analysis then aggregates these small units, forming progressively larger geographic areas of analysis, finally reaching the sub-basin (see Appendix B). Land use grid values for the Shepard Brook sub-basin for 1964 and 1974 are contained in Tables A-2 and A-3.

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* All models require some type of regionalization of data. Choice of the regions for analysis could have been along any one of a number of criteria and could have been either nodal or homogeneous. Our choice of regions for the Mill River watershed were physical rather than political or economic, and they were homogeneous rather than nodal. There is nothing that makes our choice more legitimate than any other for analysis of land use and water and air quality in the basin. Dealing with water or sewer facilities and with run off leads to the use of natural drainage patterns and logically to the use of sub-basins as the unit of analysis. For a more detailed discussion of the process of regional definition, see Tabors, R., The Definition of Multifunctional Planning Regions, Harvard University Center for Population Studies, 1971.

Collection of data was done utilizing a relatively primitive yet readily and inexpensively available method, grid cell counting. Overlay grids one-half mile to a side (160 acres) were prepared. Each grid cell was then divided into 100 cells which were counted according to the major land use type within the cell. The orientation of the grid pattern within the basin was arbitrary but consistent in following the major map boundaries of the 1963 land use study of Hamden. The grid cells within the Shepard Brook sub-basin were then labeled by number and counted. For use in the STORM model information for the other sub-basins was not required in the level of detail and location specificity of the Shepard Brook area. Nonetheless, the system of storage and ultimate use made this the most convenient method of collection for the total basin.

The land use data for the basin was collected in six categories. High density single family development (density greater than two units per acre), low density single family development (less than two units per acre), multi-family housing, commercial and institutional uses, industrial uses, urban open land and nonurban land. The categories chosen were picked because of their significance in the analysis of Hamden. The definitions might be altered for other communities.

A short note on our data collection method, grid cell counting, is required at this point. There are a number of relatively sophisticated and more accurate methods of areal data gathering. The most commonly used system is the use of a planimeter to measure the area within a set boundary. We have chosen the visual grid method because we believe that it is of sufficient accuracy for our purposes and because it is a technique that can readily be applied by a planning office to a land use problem such as the one under investigation. The equipment requirements are no more than a sheet of acetate, a straight edge, a permanent fine point marker and the patience of the planner to count and record accurately and systematically the major contents of each cell. The method is also useful in measuring permeability, feet of gutter and other runoff characteristics of each land use type (see below).

Table A-2

Shepard Brook: 1961/1962 Land Use

(Percent of Cell)

Grid No.	Cell Size*	Residential Single 1	Residential Single 2	Residential Multiple	Commercial and Institutional	Industrial	Open	Non-Urban
0	.06	50						50
1	.4							100
2	.4	38						62
3	.4							100
4	.16							100
5	.28	7.1	14.2					79
6	1.0	5			1	1		93
7	1.0	3			1		2	94
8	1.0						1	99
9	.4							100
10	.13		46					54
11	1.0	3	6					91
12	1.0	4	6		1		1	88
13	.65	25	8		6			62
14	1.0	5	3					92
15	.64	6	34		2			58
16	.17		18		6			76
17	1.0		50		1	4		45
18	.5	8	32					60
19	.2					50		50
20	.94		4		26	14	17	38
Total Basin		5%	10%		3%	2%	2%	78%

* A full cell = 1/2 mile x 1/2 mile.

Table A-3

Shepard Brook 1974 Land Use

(Percent of Cell)

Grid No.	Cell Size*	Residential			Commercial and Institutional	Industrial	Open	Non Urban
		Single 1	Single 2	Multiple				
1	.4	42.5					7.5	50
2	.4							100
3	.32							100
4	.06							100
5	.3	20						80
6	1.0	10			3	10		77
7	1.0	22			10			68
8	1.0							100
9	.33							100
10	.19		42					58
11	1.0		8		11	9	2	70
12	1.0		35		4	4	2	55
13	.73		45				11	44
14	.77		30					70
15	.88		51		8			41
16	.1		60		10		30	
17	1.0		57		7			36
18	.4		68		10		15	7
19	.2						100	
20	.94		14	17	16	13	28	13
0	.06		50					50
Total Basin		4.6%	21.3%	1.7%	4.8%	2.9%	5.8%	58.9%

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* A full cell = 1/2 mile x 1/2 mile.

The STORM model employed in our analysis requires the determination of a number of runoff characteristics of each of the land use types e.g., the amount of impervious land and the number of gutter per unit of land in each land use type must be carefully estimated for STORM. The town of Hamden again presented a convenient study area because it allowed us access to aerial photographs of the town, taken in 1963 at the time of the Goodkind and O'Dea land use plan. These photographs are at the same scale as the land use maps, 1:200. We used these to select a set of areas within each land use type which could be examined in detail to determine the quantity of roof surface and road and driveway surface per unit area. Once again the process of data extraction was not highly sophisticated. We chose a sample of cells, each equal to 1/100 of our original one-quarter square mile grids. We then again reduced the size of the counting grid by 1/100, roughly to 70 square feet. At this scale it is possible to calculate the proportion of nonpermeable surfaces associated with each land use type and to measure the feet of gutter associated with each type. Because we had used a sample of grids within each land use type, our final coefficients for impermeable area is an arithmetic average of the values calculated for the individual cells. The values derived are summarized in Tables A-4 and A-5. Like the method of deriving the proportion of each of the subbasins occupied by each land use type, our method of data manipulation for permeability was straightforward and easily applied. Previous work by those associated with the project has shown that while more sophisticated methods yield more accurate measurements, the nature of most land use studies, in which only the proportion of a land use type within a given geographic area is of concern, cannot justify the use of methods more sophisticated than those applied here. In a number of instances we have found that to arrive at this gross level of information the grid method was also more accurate given the additive nature of the measurement error inherent in many small measurements done with a planimeter or other devices.

A set of assumptions have been made about the coefficients for both perviousness and for feet of gutters. One assumption, to date untested, is that there has been no significant change in the relative proportion of pervious and impervious surface by land use type over the past 20 years. We believe this assumption is viable because, for the most part, the spatial relationships have not changed dramatically in the past years. R4 zoning is very much the same pattern today that it was 10 years ago with the possible difference that there are now fewer straight streets.

A further assumption is that the relationships

Table A-4

Impermeable Areas (%)

Land Use Type	Driveway	Roof	Road	Parking Lot	Open Storage	Percent Permeable Areas
1. Residential 1	3.0%	5.5%	12.5%	--	--	79.0%
2. Residential 2	9.5%	16.0%	21.3%	--	--	53.2%
3. Multiple family	--	5.0%	17.0%	16.0%	--	63.0%
4. Commercial*/ Institutional	--	18.0%	8.0%	40.0%	--	34.0%
5. Industrial	--	10.0%	10.0%	4.5%	34.0%	41.0%

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* Note: Includes great variation between shopping center and school.

Table A-5

Feet of Gutter per 69696 square feet
(1/100th of 1/4 sq. mile grid cell)*

Land Use Category	Feet of Gutter	Road Width
1. Residential 1**	0	20
2. Residential 2	1484	20
3. Multiple	600	40
4. Commercial/ Institutional	275	40
5. Industrial	350	40

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* Assumes gutters on both side of road where there are gutters.

** Large size lots are "rural" in nature and do not have gutters.

discovered for a given geographic area can in fact be treated as average values to be applied over considerably larger areas. Our analysis of Hamden for 1963 indicates that this assumption is robust, although considerably more sampling for other areas would be required to discover the precise limitations to scaling of the Hamden area coefficients.

The 1974 land use data of all sub-basins are summarized in Table A-6.

Other Aspects

The impervious areas are the main locations for accumulation of dust and dirt. The town of Hamden provides some streetcleaning. Dixwell, Whitney and State are state streets; they are cleaned once a year. The rest of the streets in Hamden are cleaned with brush type cleaners about 2-1/2 to 3 times a year. The efficiency of this cleaning equipment is approximately 30 to 50 percent.

Table A-6

Summary of Mill River Subbasins

Subbasin	Total Area (acres)	Open Space & Non-Urban	Developed	% Land Use Types (developed area) 1	2	3	4	5
Lake Whitney West	1286.0	190.0	1096.0	0.	46.7	10.2	28.5	14.6
Lake Whitney East	734.0	296.0	438.0	0.	92.0	0.	8.0	0.
Shepard Brook	1893.0	1245.0	648.0	13.0	60.0	4.9	14.0	8.0
Centerville & Hamden	1336.0	610.0	726.0	0.	69.1	9.6	19.0	2.2
Central Mill	869.0	688.0	181.0	24.9	23.8	0.	48.6	2.8
Eaton Brook	1467.0	1048.0	419.0	10.3	82.1	0.	7.6	0.
Northern Country Club	272.0	165.0	107.0	28.0	62.6	0.	9.3	0.
North Eastern Mill (Butterworth)	1600.0	1534.0	66.0	100.0	0.	0.	0.	0.
Willow Brook - Hickory Jepp	1936.0	1608.0	328.0	78.0	15.5	0.	5.8	0.6
Cheshire Mill	3712.0	3155.0	557.0	19.9	80.1	0.	0.	0.
Willow Brook North	6192.0	5668.0	524.0	24.0	76.0	0.	0.	0.

Land Uses: 1 = single family - low density; 2 = single family - high density; 3 = multi-family; 4 = commercial; and 3 = industrial.

Appendix B

Results from Experimental Runs with STORM

Since there are no data available for calibration and verification of STORM, our testing of the model is limited to a logical verification, i.e. checking the consistency and logic of results in response to single or simultaneous changes of parameters and input variables. Furthermore we attempted to compare STORM's results with literature values. We limit our discussion to the runoff part of STORM (quantity and quality). The universal soil loss equation (USLE) and its results have been discussed frequently.* Because the calculation of erosion is not influenced by results generated in the runoff part, but only by the rainfall input, the performance of the universal soil loss equation is independent of the performance of the other STORM segments.

The following parameters and input variables determine the performance of STORM's runoff computations:

1. Runoff coefficients for urban and non-urban areas;
2. Depression recovery coefficients;
3. Size of the area for which runoff is predicted; important questions are concerned with the resolution potential of the model when applied to small areas, and with the areal size beyond which the neglect of routing leads to obvious errors;
4. Number of land uses distinguished; data requirements, computer time, etc., are significantly affected by this choice;
5. Length of gutter/acre for each land use;
6. Accumulation rate of dust and dirt and composition;
7. Street sweeping intervals and efficiency of sweeping equipment;
8. Percent imperviousness of land devoted to each land use;

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* See, for example, the update of the User's Manual of SWMM, University of Florida, Gainesville, Feburary, 1975.

9. Precipitation data, which is particularly important when no rain gages exist near the area being investigated.

Because quantity and quality of runoff are simultaneously considered, it must be noted that all issues and parameters which affect quantity also affect quality in STORM. Parameters (5), (6) and (7) above affect STORM's calculations of quality alone.

A number of computer runs have been made to explore the sensitivity of the model to these variables and parameters. The first runs were based on modification of the original test data, as supplied by the Hydraulic Engineering Center, Davis, California, while subsequent runs utilized actual data: rain data from the airport rain gage at Bridgeport, Connecticut and land use data of Shepard Brook, one of the sub-basins of the Mill River. Detailed land use data of the 2.5 square mile sub-basin were collected from available land use maps.*

The following types of runs have been made:

1. Change of rain intensity;

2. Variations of runoff coefficients;

3. Change of percentage of imperviousness for each land use;

4. Different aggregation of land uses for continuous development;

5. Use of STORM on small individual developments; and

6. Change of accumulation rates of dust and dirt and their composition.

For most of the runs the same meteorological condition was employed, namely the 1974 precipitation record at the Bridgeport Airport. We have evaluated in detail up to five rain intervals and generated pollutographs on an hourly basis, and we have tried to obtain a representative sample of events, including brief, intensive rains with short and long dry antecedent conditions, as well as long and less intensive rains with long and short dry antecedent conditions (see Table B-1).

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* See Appendix A.

Table B-1

Rain Interval of Interest

Interval	Date	Dry Antecedent Conditions (hours)	Length of Interval (hours)	Intermediate Dry Period (hours)	Rain (inches) Event* 1	Rain (inches) Event* 2
1	Jan. 21, 74	112	32	13 (after 10 hrs)	1.63	.56
2	June 16, 74	367	3	-	.51	
3	Sept. 3, 74	35	7	-	1.11	
4	Oct. 31, 74	127	6	2 (after 2 hrs)	.08	.45
5	Dec. 1, 74	256	11	-	2.84	

* When a rain interval was interrupted by a dry period, the part before the dry period is called event 1, and the one afterward event 2.

Table B-2

Characteristics of Hypothetical Developments

	area (acres)	% imperviousness	gutter length/acre
residential	160	36.3	600
commercial	123.2	13.7	172
industrial	160	22.7	219

To simplify the presentation, two sets of test runs were chosen for detailed discussion. The first set comprises simulation of runoff from developments at a subdivisional level, the second runoff from the Shepard Brook sub-basin incorporated those developments. The second set of runs is also employed to compare different aggregations of land-use types.

In the first subset some relatively undeveloped areas of Shepard Brook were picked and subdivisions for development designed (see Table B-2 on p. B-3).

1. Residential single-family development (lot sizes smaller than 1/2 acre) (res);

2. Commercial development of a shopping center (com); and

3. Light industrial development (ind).

The base year is 1974. Table B-3 shows the resulting runoff and washoff for the rain events of interest. The calculations are at present limited to suspended solids (SS), settleable solids, BOD, nitrogen, and PO_4 emissions, because the recoding of STORM to calculate coliforms was not finished when these runs were made. Table B-3 reveals the importance of the dry antecedent conditions. Comparing intervals 1 and 2 in terms of washoff and runoff, but ignoring intensity of rain, we recognize that the washoff of suspended solids* in interval 1 is only about 1.25 times as high as in interval 2, even though the runoff of 2 is less than a quarter of the runoff of 1. But the number of dry hours preceding the rain interval is 112 hours in the former case and 367 hours in the latter. Rain interval 3 confirms these findings. Its resulting runoff of 0.27 inches generates only some 2,400 pounds compared to some 4,700 pounds generated by 0.11 inches of runoff (interval 2) because interval 3 was preceded by a dry period of only 35 hours. Clearly, an important consideration is the length and intensity distribution of the rain in each interval. Interval 2 is only 3 hours long with 1 hour of high intensity, while 1 is more evenly distributed over a much longer period. The intensity of the rain is directly related to the washoff. The 1-hour peak washoff of interval 2 comprises about three-quarters of the total washoff.

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* Our discussions are largely limited to suspended solids (SS), because discussing all pollutants at the same time is more confusing than enlightening. The tendency is basically the same.

Table B-3

Runoff and Washoff
Land Use 1974 of Shepard Brook*

Interval	Length (hours)	Rain (inches)	Runoff[1] (inches)	SS[1] (lbs)	Settleable Solids (lbs)	BOD (lbs)	N (lbs)	PO_4 (lbs)
Total		39.4	8.73	131,922	16,368	19,599	6,786	916
1	32	2.19	.54 (355.1)	6,061 (3,231)	395	759	318	34
2	3	.52	.11 (150.0)	4,729 (3,658)	500	732	240	37
3	7	1.11	.27 (130.0)	2,376 (909.8)	486	324	113	21
4	6	.53	.12 (208.0)	3,495 (3,355)	363	484	178	22

* urban area: 648 acres; non-urban: 1245 acres.

[1] Figures in parentheses are the hourly peak runoff (cfs) and maximum SS washoff, respectively of each rainfall interval.

Table B-4 summarizes the runoff and washoff of the 1974 total and of four of the five rain intervals in the three hypothetical developments. The residential area has the highest percentage of imperviousness and the greatest gutter length per acre; thus even though its accumulation rate of dust and dirt is quite low, the washoff from that area is only about two-thirds of the washoff generated in the commercial and industrial areas, while total runoff is necessarily greater. The washoff rates from the commercial and industrial areas are quite close. The comparability of these two developments is based on the fact that even though the industrial development has higher total dust and dirt accumulation rates and a larger rate of imperviousness, the commercial development has a higher proportion of the dust and dirt accumulation in the components considered. The runoff and washoff rates reveal that each single development might have a significant impact on a sub-basin.

In order to make comparative runs between sub-basins without additional development and sub-basins with additional development, the question of how to incorporate the developments into the total scheme has to be solved. In particular, the handling of the percentage of imperviousness for each affected land use has to be considered. Since the new developments do not have exactly the imperviousness of the existing land use type in the sub-basin, either the land use type's overall imperviousness has to be adjusted, or the new development's rate of imperviousness has to be adjusted to the figure of its land use type by taking away some of the pervious area and adding it to the category of open space, parks and non-urban area. These options have different impacts on the generated results, since land use types exhibit different accumulation rates. Imperviousness affects the runoff and the washoff of each category. In order to document the arising problems, the aggregation is done both ways. Table B-5 shows the results for the industrial area.

The first array of events is based on the original industrial development except that 37 acres are deleted. These have not been developed and are separated from the core industrial development by a railroad; these acres are added to the non-urban category. Since the imperviousness of the industrial area does not correspond exactly to the overall imperviousness of the industrial land use category (Table A-4), the latter is adjusted, i.e., actually reduced. In the second array, the size of the industrial development is reduced so that the new development's imperviousness is equal to the overall industrial imperviousness. This procedure cannot always be done because a new 160 acres development might have such a high imperviousness that it

Table B-4

Runoff and Washoff
Individual Developments

	Interval	Length (hours)	Rain (inches)	Runoff (inches)	SS (lbs)	Settleable Solids (lbs)	BOD (lbs)	N (lbs)	PO_4 (lbs)
Residential	Total		39.4	13.35	24,345	2,303	3,600	1,331	108
	1	32	2.19	.84	1,335	80	167	70	7
	2	3	.52	.18	809	47	126	45	5
	3	7	1.11	.42	355	64	46	19	2
	4	6	.53	.2	701	59	105	39	4
	5	11	2.78	1.12	2,435	445	295	130	13
Commercial	Total		39.4	8.13	38,784	3,709	5,759	2,066	179
	1	32	2.19	.52	2,128	128	265	110	11
	2	3	.52	.11	1,289	76	202	69	7
	3	7	1.11	.26	566	103	73	30	3
	4	6	.53	.12	1,117	95	168	59	6
	5	11	2.78	.68	3,880	716	471	205	21
Industrial	Total		39.4	10.21	35,233	3,513	5,217	2,024	165
	1	32	2.19	.68	1,933	121	240	104	10
	2	3	.52	.14	1,171	72	183	68	7
	3	7	1.07	.32	514	97	67	29	3
	4	6	.53	.16	1,014	90	152	59	5
	5	11	2.78	.86	3,525	680	427	192	19

Table B-5

Runoff and Washoff
Comparison of Different Incorporation of Industrial Development

Interval	Length (hours)	Rain (inches)	SS (lbs)	Settleable Solids (lbs)	BOD (lbs)	N (lbs)	PO_4 (lbs)
Total+		39.4	158,517	18,703	23,524	8,377	1,039
1	32	2.19	7,637	491	954	403	42
2	3	0.52	5,579	531	865	293	41
3	7	1.11	2,719	546	367	134	22
4	6	.53	4,292	427	645	233	27
Total++		39.4	142,501	17,248	21,157	7,381	966
1	32	2.19	6,684	431	837	350	37
2	3	0.52	5,068	512	785	259	39
3	7	1.11	2,514	509	342	121	21
4	6	.53	3,811	387	573	203	25

+ urban area: 694 acres; non-urban area: 1199 acres.

++ urban area: 771 acres; non-urban area: 1122 acres.

could not be adjusted to the overall proportion. The first arrangement yields higher washoffs; this is explainable from the fact that even though the rate of imperviousness is lower than in the second arrangement, the factor, gutter/acre which influences dust and dirt accumulation, is kept constant Thus the second arrangement yields a lower washoff rate because the reduction of acreage also reduces the total gutter area. Thus if the largely pervious land use category (i.e., parks, open space and non-urban) could be divided into a number of different pervious land uses, the analysis could be better tuned; but computer costs and manpower resources (to collect the necessary data) increase steadily, so that the non-urban land uses should only be subdivided if size and diversity warrant such an extension of the analysis.*

Both types of runs are also made after incorporation of all the hypothetical developments in Shepard Brook (Table B-6). The first set of results is obtained by keeping the original development areas and adjusting the overall imperviousness, while the second is obtained by adjusting the development areas such that the assumed overall imperviousness rates are met. These runs are of interest because the addition of commercial and industrial areas could be easily envisioned after a large residential development had been built, or vice versa. The planner might work through these possibilities for additional interpretation of the impact of each single development. Table B-6 shows that total emission increases significantly beyond the emission level of the base year 1974 (see Tables B-3 and B-6). The actual difference in the washoff rate is influenced by the method of aggregation applied; this is particularly true for SS and BOD. The results confirm the tendency emerged in Table B-5.**

Now another type of comparison is presented. The simulation is run separately for individual development, for example, residential or commercial, and for the entire sub-basin without the development. Another run is then made for the entire sub-basin including the new development.

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* Considering the accuracy of the model, we do not feel the differences are very significant in this case.

** Runoff has not been considered because the program yields just results in inch/area, but not the total amount, adjusted to the ratio of urban to non-urban areas.

Table B-6

Runoff and Washoff
All Hypothetical Developments Incorporated in Shepard Brook

Interval	Length (hours)	Rain (inches)	SS (lbs)	Settleable Solids (lbs)	BOD (lbs)	N (lbs)	PO_4 (lbs)
Total[+]		39.4	212,263	23,041	31,466	11,386	1,286
1	32	2.19	10,830	678	1,352	570	58
2	3	.52	7,293	587	1,134	390	48
3	7	1.11	3,409	660	453	174	24
4	6	.53	5,902	550	888	322	35
Total[++]		39.4	167,835	19,153	24,900	9,868	1,072
1	32	2.19	8,250	522	1,031	434	45
2	3	.52	5,858	526	909	308	42
3	7	1.11	2,816	556	378	140	22
4	6	.53	4,586	444	690	248	28

[+] urban area: 1031 acres; non-urban area: 861 acres.

[++] urban area: 880 acres; non-urban area: 1013 acres.

It has been felt that a desirable property of the model is linear additivity. That is, the sum of emissions as well as runoff calculated for the development and basin individually should equal (approximately) the total emissions and runoff, respectively predicted by aggregate analysis. Table B-7 indicates that this is indeed the case.

There are also runs performed for the 1974 land use utilizing the accumulation rates and composition derived from the calibration exercises in Castro Valley.* Table B-8 reveals the necessity of good calibration or intuitive derivation of the parameters because increased accumulation rates significantly influence the runoff quality of an area (compare Tables B-3 and B-8).

Table B-9 displays portions of pollutographs of the intervals 1 and 2. It shows how the washoff is closely related to the intensity of the rain and to the time elapsed from the start. It also reveals that the total load washed into the receiving water body is of a significant size, while, with a few exceptions, the concentrations of all pollutants except SS are not very high. The concentration of BOD_5 in event 2 is close to the BOD_5 of a secondary treatment plant's effluent. These pollutants are based on the Chicago values for dust and dirt accumulation and composition; it is obvious that the pollutographs for these events would be characterized by higher concentration if the Castro Valley parameters are employed.

Finally, some runs are made to compare the impact of different street sweeping strategies. The frequency of sweeping is increased to once a week in commercial and industrial areas and to once every two weeks in residential areas. In a second run the sweeping efficiency of the equipment was improved in addition to the increased frequency of sweeping. Comparing the washoff from Shepard Brook for the prevailing situation** (Table B-3) with the results in Table B-10 shows that these strategies cause a

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* See section 5, Table 5-8; data are reported in Roesner, et al., "A Model for Evaluating Runoff-Quality in Metropolitan Master Planning," ASCE Urban Water Resources Research Program, Technical Memorandum No. 23, April, 1974, p. 62.

** See Appendix A.

Table B-7

Runoff and Washoff[1]
Check on Linear Additivity

Land Use	Runoff (inches)	SS (lbs)	Settleable Solids (lbs)	BOD (lbs)	N (lbs)	PO_4 (lbs)
R1	8.56	128,802	15,590	19,119	6,676	867
R2	13.35	24,345	2,303	3,600	1,331	108
Σ		153,147	17,893	22,719	8,007	973
R3	8.9*	150,851	17,693	22,371	7,902	992

[1] All results are totals for 1974 precipitation.

R1 1974 land use (urban: 648 acres; non-urban: 1245 minus 160 acres).

R2 Individual residential development of 160 acres.

R3 1974 land use incorporating residential development (urban: 808 acres; non-urban: 1085 acres).

* Runoff is compared by weighting the runoff with the corresponding areas:

$$8.56 * 1733 + 13.35 * 160 \sim 8.9 * 1893$$
$$16985 \sim 16850$$

Table B-8

Runoff and Washoff[1]
Shepard Brook 1974: Increased Accumulation Rate of Dust and Dirt

Interval	Length (hours)	Rain (inches)	Runoff (inches)	SS (lbs)	Settleable Solids (lbs)	BOD (lbs)	N (lbs)	PO_4 (lbs)
Total		39.4	8.73	302,561	44,195	69,969	16,693	2,921
1	32	2.19	.55 (.05)	15,976 (1,566)	2,002 (258)	3,090 (649)	824 (103)	150 (22)
2	3	.51	.12	8,402	924	2,168	494	78
3	7	1.07	.28 (.1)	5,907 (2,882)	1,008 (473)	1,037 (568)	293 (149)	56 (28)
4	6	.53	.13 (.01)	7,070 (361)	867 (66)	1,731 (20)	417 (29)	62 (6)
5	11	2.84	.73 (.09)	31,457 (5,329)	6,254 (710)	5,206 (1,543)	1,621 (315)	263 (58)

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[1] Figures in parentheses reflect runoff and washoff in the first four hours of the interval; interval 2 lasted less than four hours.

Table B-9

Hourly Runoff and Washoff from New Residential Development Incorporated in Lande Use 1974*

(Urban: 808 acres; Non-urban: 1,085 acres)

Date (begin)	Hours of runoff from start	Rain (inches)	Runoff (inches)	SS (lbs)	Settleable Solids (lbs)	BOD (lbs)	N (lbs)	PO_4 (lbs)
January 21/74 (9 a.m.)	3	.06	.02	154.9	6.3	33.3	9.4	1.0
			(30.8)	(22.4)	(0.9)	(4.8)	(1.36)	(0.15)
	4	.08	.02	228.1	8.7	41.0	13.1	1.4
			(41.0)	(24.7)	(0.9)	(4.4)	(1.42)	(0.15)
	5	.31	.08	1655.5	64.9	201.8	86.3	8.9
			(159.0)	(46.3)	(1.8)	(5.6,	(2.42)	(0.25)
	6	.12	.03	294.7	12.8	35.5	15.2	1.6
			(61.5)	(21.3)	(0.9)	(2.6)	(1.10)	(0.12)
	7	.71	.19	3420.8	265.6	357.5	173.9	17.8
			(364.1)	(41.8)	(3.2)	(4.4)	(2.13)	(.22)
	8	.09	.02	37.2	5.1	4.1	1.9	0.2
			(46.1)	(3.6)	(0.5)	(0.4)	(0.18)	(0.02)
	9	.07	.02	24.9	3.7	2.8	1.2	0.2
			(35.9)	(3.1)	(0.5)	(0.3)	(0.15	(0.02)
June 16/74 (6 p.m.)	1	.2	.03	1016	78	210	59	7.5
			(50.1)	(90.3)	(6.9)	(18.7)	(5.25)	(0.67)
	2	.3	.08	3800	411	535	188	29.5
			(153.8)	(109.3)	(11.9)	(15.5)	(5.44)	(0.9)
	3	.02	.01	101.6	18.4	16.6	4.6	1.1
			(10.3)	(44.1)	(8.0)	(7.2)	(2.01)	(.48)

* Figures in parentheses describe the peak runoff (in cfs) and the resulting concentration (mg/l), respectively.

Table B-10

Comparison of Street Cleaning Strategies
Shepard Brook: Land Use 1974*

	SS (lbs)	Settleable Solids (lbs)	BOD (lbs)	N (lbs)	PO_4 (lbs)
Total[+]	109,143	13,043	16,653	5,204	766
January	4,163	278	526	211	23
June	3,078	392	388	93	23
September	2,225	409	397	146	24
October	2,814	252	259	45	9
December	10,293	1,742	1,280	500	72
Total[++]	96,024	11,516	14,799	4,524	688
January	2,923	191	390	149	17
June	2,090	336	284	66	20
September	2,147	374	380	137	23
October	2,426	203	243	41	9
December	9,227	1,473	1,153	444	67

* See Table B-3 for comparison of existing strategy.

[+] Increased sweeping frequency: commercial and industrial areas: 1/wk; residential areas: 1/2 wks.

[++] Additional increase of sweeping efficiency: 70%.

significant reduction in washoff.*

Table B-11 compares our 1974 Shepard Brook yields (pounds/acre/year), based on the Chicago values of accumulation and composition, to values reported for Cincinnati and San Francisco. It is difficult to compare loading figures of different cities for different years, when no details are known about the way these figures were arrived at. Such a comparison is to develop a feeling for the orders of magnitude involved. Except for all SS yields and the BOD yields from San Francisco, values from the urban part of Hamden are comparable to the other cities in order of magnitude.

In general, we believe that our limited number of runs demonstrate the potential of STORM as a planning tool for estimating the order of magnitude of pollution, but also indicate that it does not come close to the accuracy required of a design tool.

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* Based on these results, an economic comparison of various strategies for reducing the load of washoff to receiving streams might be undertaken.

Table B-11

Comparison of Results from STORM and Literature

	SS	Settleable Solids	BOD	N	PO_4
Total (lbs) Shepard Brook	131,922	16,368	19,589	6,786	916
Urban Total (lbs)+	107,681	10,298	16,101	5,443	533
Urban Yield++ (lbs/acre/yr)	166	16	25	8.4	0.9
Cincinnati* (lbs/acre/yr)	730	-	33	8.9	2.5
San Francisco** (lbs/acre/yr)	632 540	- -	101 136	10.6 15.6	2.4 3.2

+ The total yearly yields and the total yearly urban yields from Shepard Brook are computed by STORM for 1974.

++ 648 acres are urban acres (Land Use 1974); dividing the total urban yields by the urban area gives the urban yield in lbs/acre/yr.

* Weibel, *et al.*, Urban Land Runoff as a Factor in Stream Pollution, *J. of Water Pollution Control Federation*, Vol. 36, 1964.

** Eckhoff, D. W., A. O. Friedland, and H. F. Ludwig, Characterization and Control of Combined Sewer Overflows, San Francisco, *Water Research*, Vol. 3, No. 7, July 1969; note: figures for two sampling areas are presented in this paper.

Appendix C

Review of Control Options for Stormwater Management by STORM*

Controls of watershed runoff and the pollutants contained in that runoff take many forms and can be applied over a wide range of drainage areas. For example, in the control of stormwater runoff, one can apply strategies ranging from ponding in individual house lots to the construction of large basins serving many square miles. A major problem, then, is to delineate those options which are candidates for inclusion in the planning analysis. It appears that the choice of control options must be based on answers to the following questions:

1. Which options will produce a significant difference in the runoff model, i.e., STORM? This question relates in part to selection of the scale of development. In any case, it is clear that it makes no sense to include options to which the model is relatively insensitive.
2. What are the major tradeoffs? Theoretically the stormwater control decision represents a tradeoff between investment in storage and transport (conveyance systems), while sediment control decisions involve tradeoffs between investment in reducing erosion and removing sediment (resulting from erosion). But within these broad categories there remains a large number of options, many of which do not fit into simple categorization. The availability of cost data for all possible options is also a problem. Since major interest in non-point sources is fairly recent, the literature is still relatively sparse on technical and cost details.
3. What are the design standards for stormwater erosion and sediment control facilities? At one point in the project, a design goal of maintaining

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* This appendix is a summary of a lengthy memorandum on non-point source controls (7 April, 1975).

> the natural unit hydrograph was discussed. The EPA,* on the other hand, talks about maintaining the peak of the natural unit hydrograph, but not the total quantity of runoff. Also, there is a growing tendency on the part of states and municipalities to place higher standards on the practices of developers with regard to non-point pollution, particularly sediment.** Ideally an analysis could be devised which indicates the proper level of performance standard to place on developments; realistically, however, only a few combinations of control options can be considered in an analysis, based on our suggested tools. Thus, it will be important, for instance, for a planning department to establish a reasonable number of control options; one of which should then be chosen as a performance standard for the particular development.

We have briefly summarized a number of the available control methods and suggest how they may be incorporated within the model framework of STORM. In listing some of the available physical control options, we have considered only two objectives: control of sediment and control of stormwater runoff rates. There are a number of other pollutants associated with stormwater runoff which present serious problems for water quality. However, at the present time the methodologies exist for handling only the two components mentioned. To some extent these methods also help to control the other pollutants, but we do not expect these problems to be eliminated simply because sediment and runoff rates are adequately controlled.

In our summary we have identified three functional areas of control within the two objectives: erosion control, sediment removal, and stormwater control. By erosion control we mean measures designed to prevent the removal and suspension of soil particles by storm events. Sediment removal processes are designed to remove sediment particles after suspension has occurred. Stormwater control refers to any method for altering the timing, quantity or rate of runoff from a site. To some extent this division is artificial, since there are clearly interactions between the different types of controls. Erosion and sediment control techniques are complementary; any comprehensive strategy must consider and include measures from both sets of controls in order to obtain acceptable performance. Similarly, many erosion and sediment-control methods alter the quantity or timing of runoff and therefore act as stormwater control devices as well. Despite these interactions, we have found it useful to adopt the present classification scheme from an EPA* report on control of non-point source pollution.

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* U. S. Environmental Protection Agency, "Processes, Procedures and Methods to Control Pollution Resulting from All Construction Activity," October, 1973.

** In Virginia, for example, developers must submit and gain approval of a sediment control plan prior to initiating development.

Each of the tables presents a different set of control methods: Table C-1 for stormwater control, Table C-2 for erosion control, and Table C-3 for sediment control. For each method we have listed specific control mechanisms (by mechanism we mean a physical effect such as detention, infiltration, reduction of velocity, etc.), the secondary impacts of the method, and some adjustments of STORM which would reflect the particular control method.** Clearly, in a crude model, such as STORM, various combinations of adjustments would constitute a particular control method. Therefore, a list can never be complete, but only suggestive to an experienced planner.

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* _Ibid_.

** Note, an S in parentheses indicates that parameters of the runoff module are changed; a U indicates that parameters of the erosion module, i.e., the Universal Soil Loss Equation, are adjusted.

Table C-1
Stormwater Control Methods

Method	Principal Control Mechanisms: Detention	Principal Control Mechanisms: Infiltration	Secondary Impacts	Method of Modeling in STORM
Rooftop Storage	X		increased costs of roof construction	storage option(s)
Parking Lot - Storage	X		inconvenience to users of facility, sediment control	storage option(s) sediment trapping ratio(u)
Parking Lot - Infiltration		X	sediment control	diversion option(s) adjust runoff coeff.(s)[1] sediment trapping ratio(u)
Detention Basins wet/dry multi/single purpose	X		sediment control, possible recreation use, aesthetic problems, potential dangers for small children, high maintenance costs	storage option for dry detention basins(s); also for wet basins in case of similar control rules(s)
On lot ponding and seapage systems	X	X	sediment control, inconvenience to homeowner	storage option(s) diversion option(s) sediment trapping ratio(u)
Storage in sewers	X		greater complexity of operating system, groundwater pollution	storage option(s)
Porous Pavements	X	X	potential groundwater pollution	depression storage(s) diversion option(s) adjust runoff coeff.(s)[2]

[1] Adjusting the runoff coefficient seems to be justifiable only when the runoff modeling is limited to the commercial (or industrial area) with the parking lot as major portion of the total area.

[2] Only justifiable when the porous pavement makes up a major part of the "impervious" area.

Table C-2
Erosion Control Methods

	Principal Control Mechanisms				
Method	Soil Stabilization	Flow Modification	Diversion	Secondary Impacts	Method of Modeling in STORM
surface roughening		X		increases infiltration, provides base for mulching	diversion factor(s) soil erodibility factor(u) control practice factor(u)
Diversion ditches			X		diversion option(s) control practice factor(u)
Chutes and Flumes			X		diversion option(s) control practice factor(u)
Level spreaders		X			control practice factor(u)
Vegatative Stabilization	X	X		increases infiltration	diversion option(s) cover index factor(u) runoff coeff.(s)
Non-vegatative stabilization	X	X		mulch increases infiltration, inorganic binders decrease infiltration	diversion option(s) cover index factor(u) cover index factor runoff coeff.(s)
Grade stabilization		X			slope-lenth factor(u)

Table C-3
Sediment Control Methods

Method	Principal Control Mechanisms		Secondary Impacts	Methods of Modeling in STORM
	Settling	Filtration		
Storm drain				
filters	X	X	frequent cleaning required	sediment trapping ratio(u) diversion option(s)
traps	X			
Straw or hay bales	X		control of peak runoff	cover index factor(u) sediment trapping ratio(u) storage option(s)
Earth dikes	X	X	control of peak runoff	sediment trapping ratio(u) storage option(s) diversion option(s)
Sediment Basin wet/dry	X		control of peak runoff, may be converted to permanent stormwater control basin	sediment trapping ratio(u) storage option(s)[1]

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[1] Largely for a dry basin

Appendix D

Lateral Sewer Cost Estimates

Tables D-1 through D-10 detail the sanitary sewer cost estimates for our ten hypothetical developments. These costs are broken down into several major subcomponents: the costs listed for street pipes and service lines include purchase of the pipe, transportation costs, and costs of installation in the trench; the house connection costs refer to the tee and y sections and elbows used to connect the service lines to the lateral and include both purchase and installation; sheeting costs are the costs of installing wood bracing and sheeting in the trenches; manhole costs cover the purchase and installation of manhole sections and cover; and excavation costs cover both the costs of digging the trenches and backfilling them after the lines are installed.

The high-density development (D-10) has by far the lowest costs of the developments analyzed; however, this result somewhat exaggerates the economies of high-density development. In the large 20-story apartments the horizontal sewer collection system has been replaced by an internal, vertical infrastructure. The costs of this extensive plumbing network are not reflected in our estimates. Also our estimates do not include the higher costs imposed on trunk and interceptors by the larger loads generated; thus the data on subdivisions should not be used directly for economic comparisons among different development types. This is the purpose of the fiscal impact model developed in this study.

The proportion of total costs which is attributed to each of the major components varies significantly depending upon the nature of the topography. This variation is made clear in the summary graph of Figure D-1. Here we have collapsed the cost breakdowns into four components: pipes (including connecting sections), sheeting, manholes, and excavation. The graphs are based upon the averages of projects in the associated slope categroies.* For the flat and steep slopes sheeting and bracing costs are by far the most important, accounting for about 60 percent and 54 percent of the total costs, respectively, while pipe costs are about 25 to 30 percent of the total. In the moderate slope case the situation is reversed, with pipe costs accounting for over 60 percent of the total and sheeting reduced to only 13 percent. The difference, of course, is due to the shallow trenches possible with favorable topography, eliminating the need for extensive bracing. Manhole and excavation costs also account for a higher proportion of the total costs in the moderate slope case for the same reason (but in absolute terms excavation costs are greater for the flat and steep topography; it is just that they are overwhelmed by the sheeting component). Overall, manholes account for 9-16 percent of the total, excavation for 4-9 percent.

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* Project 10 was not included in these calculations because its design is so different from the others.

TABLE D-1 - COST SUMMARY - DESIGN 1

540 Single Family, Conventional units
180 Acres
Flat Slope

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	28,745	99,752
service lines	LF	16,200	43,902
house con-nections	#	540	35,489
sheeting	SF	507,780	756,490 (492,610)*
manholes	#	152	83,501
		SUBTOTAL	1,019,134 (755,254)*

* Hard Clay and Shales.

Excavation = 47,386 CY
(36,311)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	1,060,351	1,061,208	788,053
COSTS/DU ($)	1,964	1,965	1,459

TABLE D-2 - COST SUMMARY - DESIGN 2

471 Single Family, Conventional
160 Acres
Moderate Slope

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	28,410	96,310
service lines	LF	16,485	44,674
house con--nections	#	471	17,705
sheeting	SF	22,661	41,373 (10,831)*
manholes	#	101	44,226
		SUBTOTAL	244,288 (213,746)*

* Hard clay and shales.

Excavation = 43,151 CY
(24,405)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	280,103	281,398	235,222
COSTS/DU ($)	595	597	499

TABLE D-3 - COST SUMMARY - DESIGN 3

471 Single Family, Conventional
160 Acres
Steep Slope

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	28,410	96,310
service lines	LF	16,485	44,674
house con-nections	#	471	20,226
sheeting	SF	153,753	293,669 (205,316)*
manholes	#	101	51,800
		SUBTOTAL	506,679 (418,326)*

* Hard Clay and Shales.

Excavation = 45,139 CY
(28,768)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	545,047	546,853	444,217
COSTS/DU ($)	1,157	1,161	943

TABLE D-4 - COST SUMMARY - DESIGN 4
359 Single Family, Conventional
652 Townhouses
207 Garden Apartment units
Flat Slope, 160 Acres

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	31,710	111,076
service lines	LF	19,115	52,046
house con-nections	#	1,023	66,536
sheeting	SF	395,268	754,961 (442,545)*
manholes	#	139	72,825
		SUBTOTAL	1,057,444 (745,028)*

* Hard Clay and Shales.

Excavation = 45,451 CY

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	1,096,131	1,097,687	785,876
COSTS/DU ($)	900	901	645

TABLE D-5 - COST SUMMARY - DESIGN 5

553 Single Family, Compact
615 Townhouses
396 Garden Apartment units
Moderate Slope, 205 Acres

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	33,975	120,334
service lines	LF	38,415	105,152
house con-nections	#	1,182	24,054
sheeting	SF	64,398	123,000 (32,199)*
manholes	#	138	62,421
		SUBTOTAL	434,961 (344,160)*

* Hard Clay and Shales.

Excavation = 68,181 CY
(39,570)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	491,548	439,596	378,981
COSTS/DU ($)	314	316	242

TABLE D-6 - COST SUMMARY - DESIGN 6

367 Single Family, Conventional
590 Townhouses
300 Garden Apartment units
Steep Slope, 160 Acres

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	30,740	104,209
service lines	LF	27,300	74,051
house con--nections	#	967	60,302
sheeting	SF	395,308	755,038 (583,372)*
manholes	#	146	97,617
		SUBTOTAL	1,091,217 (919,551)*

* Hard Clay and Shales.

Excavation = 60,603 CY
(43,365)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	1,143,472	1,145,875	959,014
COSTS/DU ($)	910	912	763

TABLE D-7 - COST SUMMARY - DESIGN 7

300 Single Family, Compact — Flat Slope
276 Townhouses — 160 Acres
540 Garden Apartment units
1040 Medium Rise Apartment units

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	22,075	98,022
service lines	LF	20,020	54,853
house con-nections	#	585	48,169
sheeting	SF	350,552	669,555 (445,301)*
manholes	#	77	45,676
		SUBTOTAL	916,275 (692,021)*

* Hard Clay and Shales.

Excavation = 42,789 CY
(32,469)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	953,675	955,394	721,568
COSTS/DU ($)	442	443	335

TABLE D-8 - COST SUMMARY - DESIGN 8

359 Single Family, Compact
417 Townhouses
696 Garden Apartment units
1290 Medium Rise Apartment units

Moderate Slope
205 Acres

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	28,980	108,067
service lines	LF	25,630	70,426
house con-nections	#	807	30,448
sheeting	SF	61,190	116,872 (36,235)*
manholes	#	116	53,225
		SUBTOTAL	379,038 (298,401)*

* Hard Clay and Shales.

Excavation = 52,058 CY
(30,390)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	422,267	423,828	325,164
COSTS/DU ($)	153	153	118

TABLE D-9 - COST SUMMARY - DESIGN 9

227 Single Family, Conventional
233 Townhouses
576 Garden Apartment units
1120 Medium Rise Apartment units

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	27,265	83,117
service lines	LF	16,009	44,637
house con--nections	#	486	18,269
sheeting	SF	74,519	142,331 (77,443)*
manholes	#	76	35,272
		SUBTOTAL	323,626 (258,738)*

* Hard Clay and Shales.

Excavation = 38,890 CY
(23,225)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	356,683	357,850	279,389
COSTS/DU ($)	165	166	130

TABLE D-10 - COST SUMMARY - DESIGN 10

4000 High Rise Dwelling Units
160 Acres
Flat Slope

ITEM	UNITS	QUANTITY	COST ($)
street pipe	LF	2,380	28,441
service lines	LF	440	2,763
house con- -nections	#	connected at manholes	
sheeting	SF	10,661	19,417 (5,083)*
manholes	#	12	5,653
		SUBTOTAL	56,274 (41,940)*

* Hard Clay and Shales.

Excavation = 2,964 CY
(1,844)*

	loam, sand, loose gravel	compacted gravel and till	hard clay and shales
TOTAL COSTS ($)	58,735	58,824	43,581
COSTS/DU ($)	15	15	11

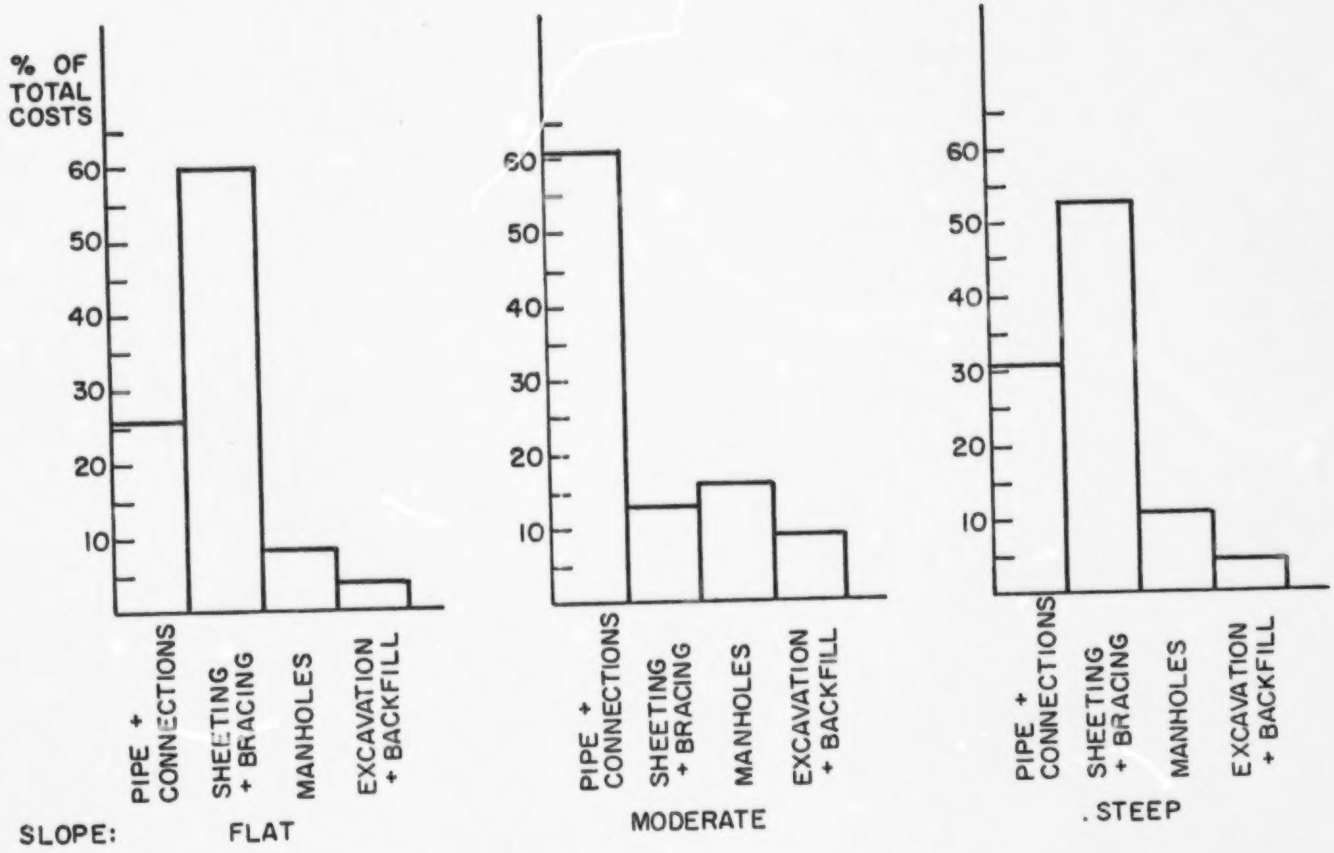

Figure D-1: Breakdown of Sewer Costs

Appendix E

Glossary

Combined Sewer: A sewer which carries both wastewater and water.

Degree Days: Sum of negative departures of average daily temperature from 65° F; used to determine demand for fuel for heating purposes.

Detention: The temporary storage of stormwater in order to regulate the amount of flow in the transport system.

Dependent Variable: Variable whose values are functionally determined by the independent variable.

Elasticity: The elasticity of variable x with respect to variable y is the percent change in the value of x associated with a one percent change in the value of y.

Emissions: Effluents discharged into the environment, specified as weight per unit time for a given pollutant from a given source.

House Connection: A pipe which conveys wastewater from a structure to the sewer system.

Hydraulic Radius: A measure of the depths of flow in a conduit or channel; more formally it is the cross-sectional area of flow divided by the perimeter of the channel in contact with the fluid.

Independent Variable: Variable which can be directly manipulated.

Infiltration: The water entering the sewer system and connections from the ground.

Intercepting Sewer (interceptor): The final sewer line in a collection system, leading to the treatment plant.

Invert: The lowest point on the inside of a sewer or other closed conduit.

Land Use Mix: The portions of a region allocated to specific land use types.

Lateral Sewer: A sewer which receives wastes only from the house connections.

Loadograph: A graph of pollutant load as a function of time over the runoff period.

Main Sewer: A sewer which receives wastes from several other sewer lines.

Module: For the purpose of this report a computational package which can be independently manipulated.

Non-Point Source: For the purpose of this report all runoff sources from non-urban activities.

Non-Stationary Source: Mobile activity which produces air pollutant emissions.

Overflow: Excess flow discharged from a sewer which is overloaded.

Point Source: Source of liquid discharge, as defined in Section 502(14), Public Law 92-500, October, 1972.

Pollutograph: A graph of pollutant concentration as a function of time over the runoff period.

Residential Density: The number of persons per unit of residential land area. Net density includes only occupied land while gross density includes in the computation unoccupied portions of residential areas, such as roads and open space.

Residual: Byproduct of activity which is released into the environment.

Retention: The storage of stormwater to prevent it from entering the sewer system; may be temporary or permanent.

Runoff: That portion of precipitation or irrigation which is not absorbed by the deep strata but finds its way into the stream.

Sanitary Sewer: A sewer which carries only wastewater and low volumes of ground-, storm- and surface water, which are not admitted intentionally.

Slope: The inclination of the ground surface or structure (such as a sewer line). Generally expressed in number of units of rise (or fall) per unit of horizontal distance.

Stationary Source: Activity at fixed location which produces air pollutant emissions.

Storm Sewer: A sewer that carries stormwater and surface water, street wash and other wash waters, but excludes domestic wastewater and industrial wastes.

Storm Sewer Discharge: Flow from a storm sewer that is discharged into a receiving water.

Stormwater Runoff: Precipitation that falls onto the surfaces of roofs, streets, grounds, etc., and is not absorbed or retained by those surfaces, but collects and runs off, eventually reaching a sewer, stream or another body of water.

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